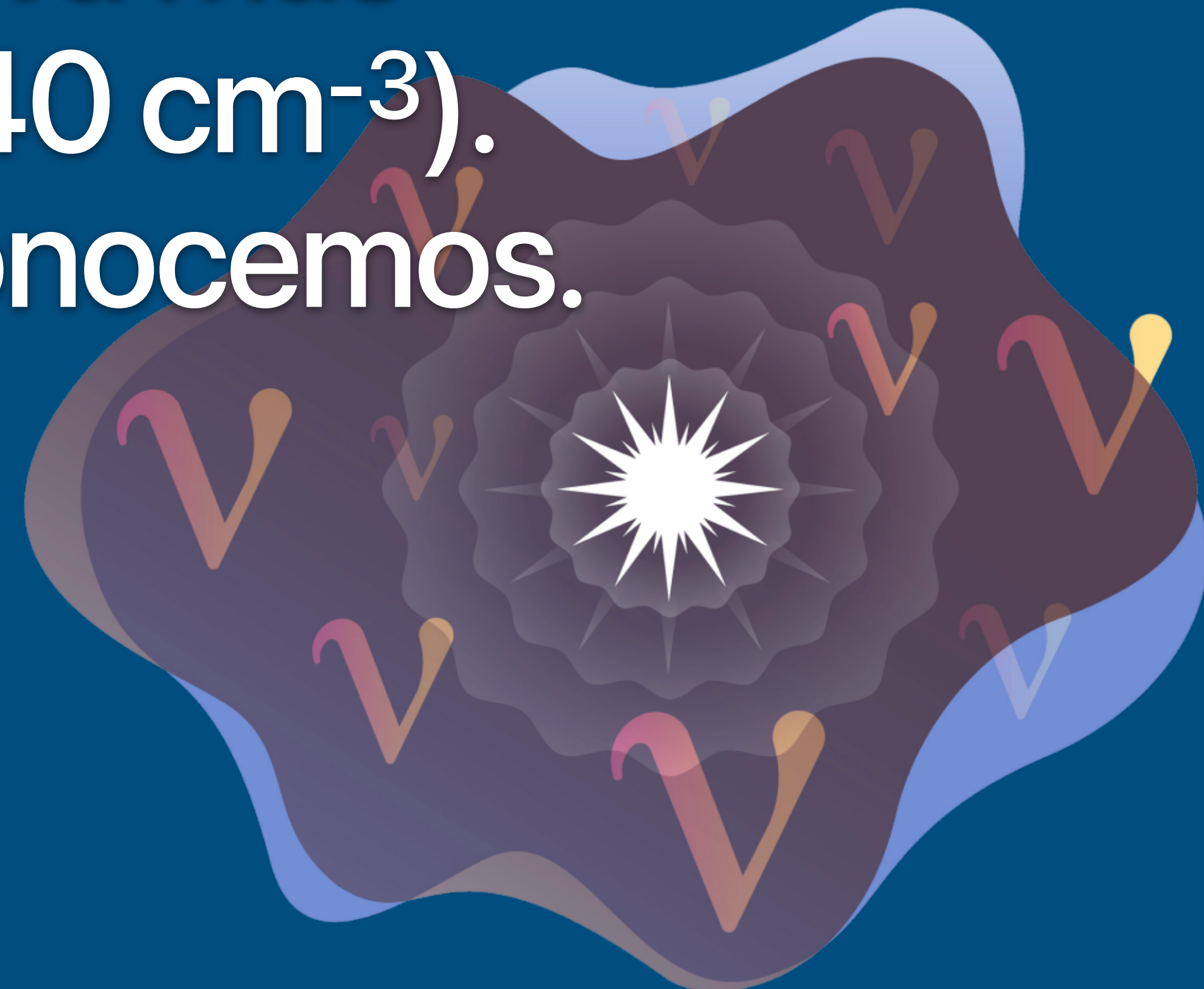


Majorana Neutrinos and the Hunt for Neutrinoless Double Beta Decay with @next

Justo Martín-Albo (IFIC, CSIC–UV)

El neutrino es la partícula masiva más abundante en el universo ($\sim 340 \text{ cm}^{-3}$). Sin embargo, es la que peor conocemos.



Sabemos que los neutrinos tienen masa...

Pero ¿cuál es su escala absoluta y cómo se ordenan? ¿Por qué son tan ligeros? ¿Cuál es el origen y naturaleza de sus masas?

Sabemos que los neutrinos oscilan...

Pero ¿violan la simetría carga-paridad (CP)?

¿Existen más de tres estados masivos?

¿Cuál es el origen de la mezcla de neutrinos?

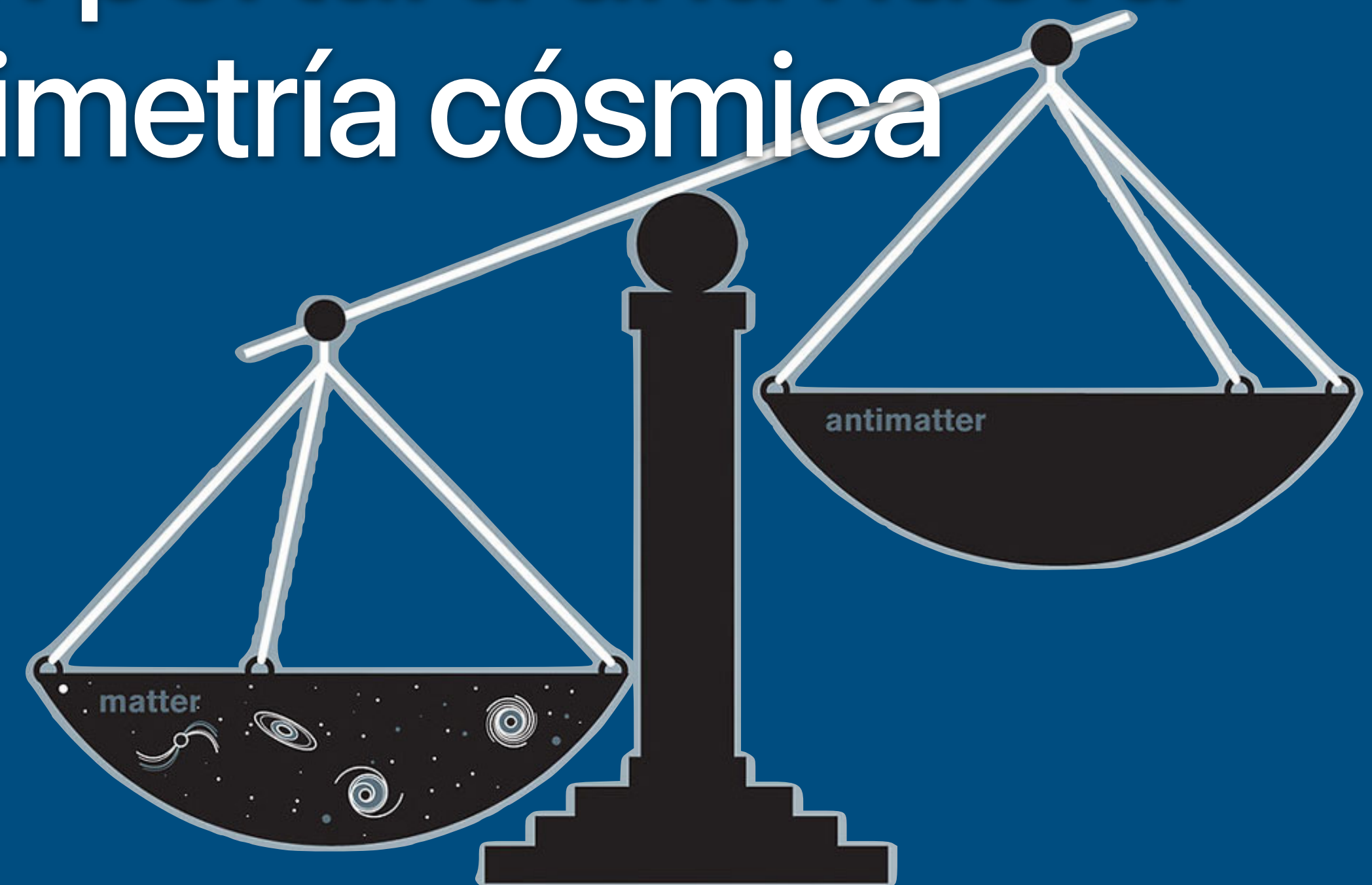
Ninguna técnica experimental por sí sola puede responder todas las preguntas.

Las oscilaciones revelan cómo se mezclan los neutrinos, pero no nos dicen nada sobre la naturaleza de sus masas.

La desintegración doble beta nos permite determinar su naturaleza, pero no si violan CP.

Además...

Los neutrinos podrían ser un portal a una nueva escala física o explicar la asimetría cósmica entre materia y antimateria.



@next

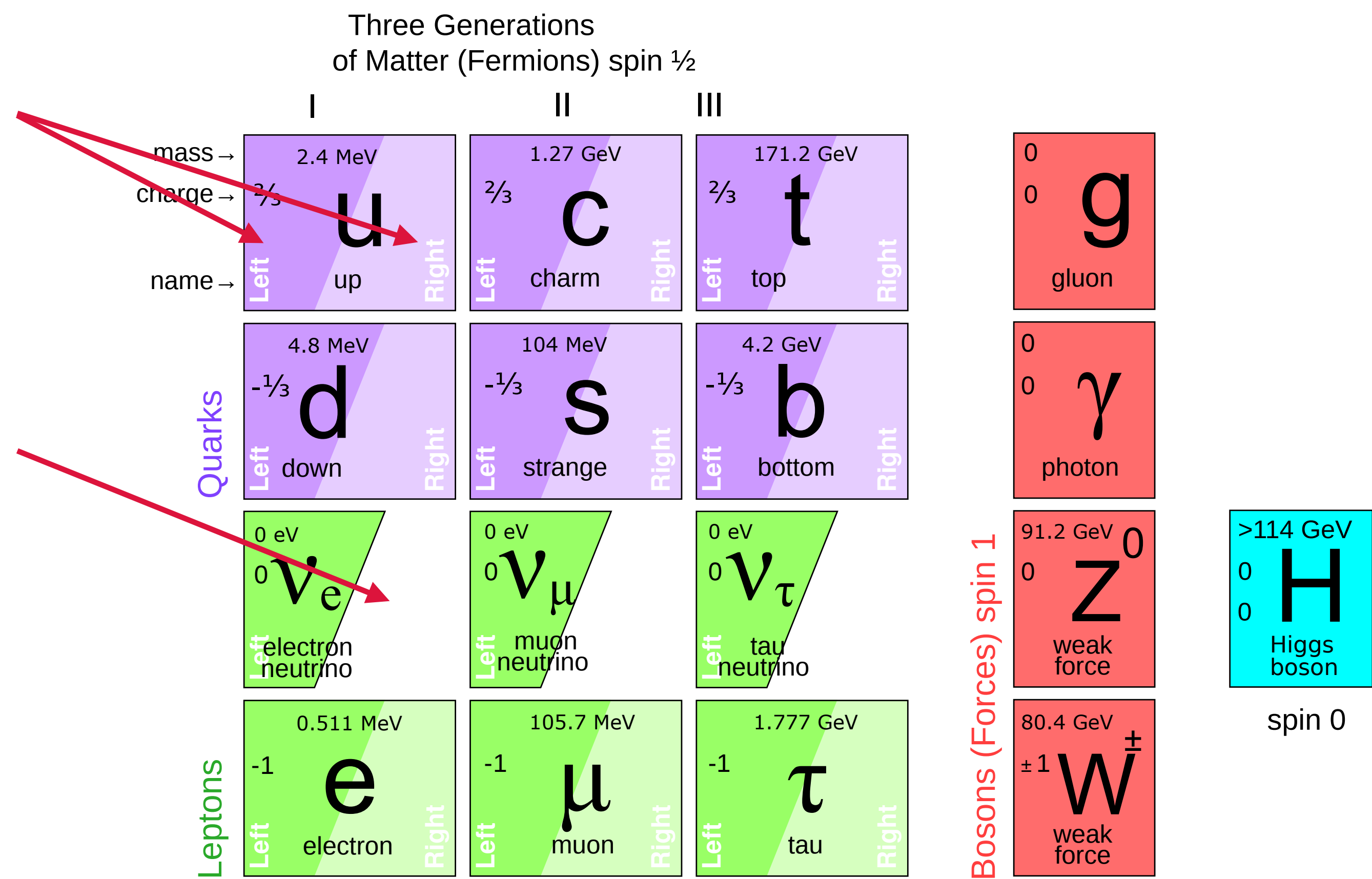


Neutrinos in the Standard Model

Fermion masses arise from the couplings of their left-handed and right-handed fields to the Higgs field.

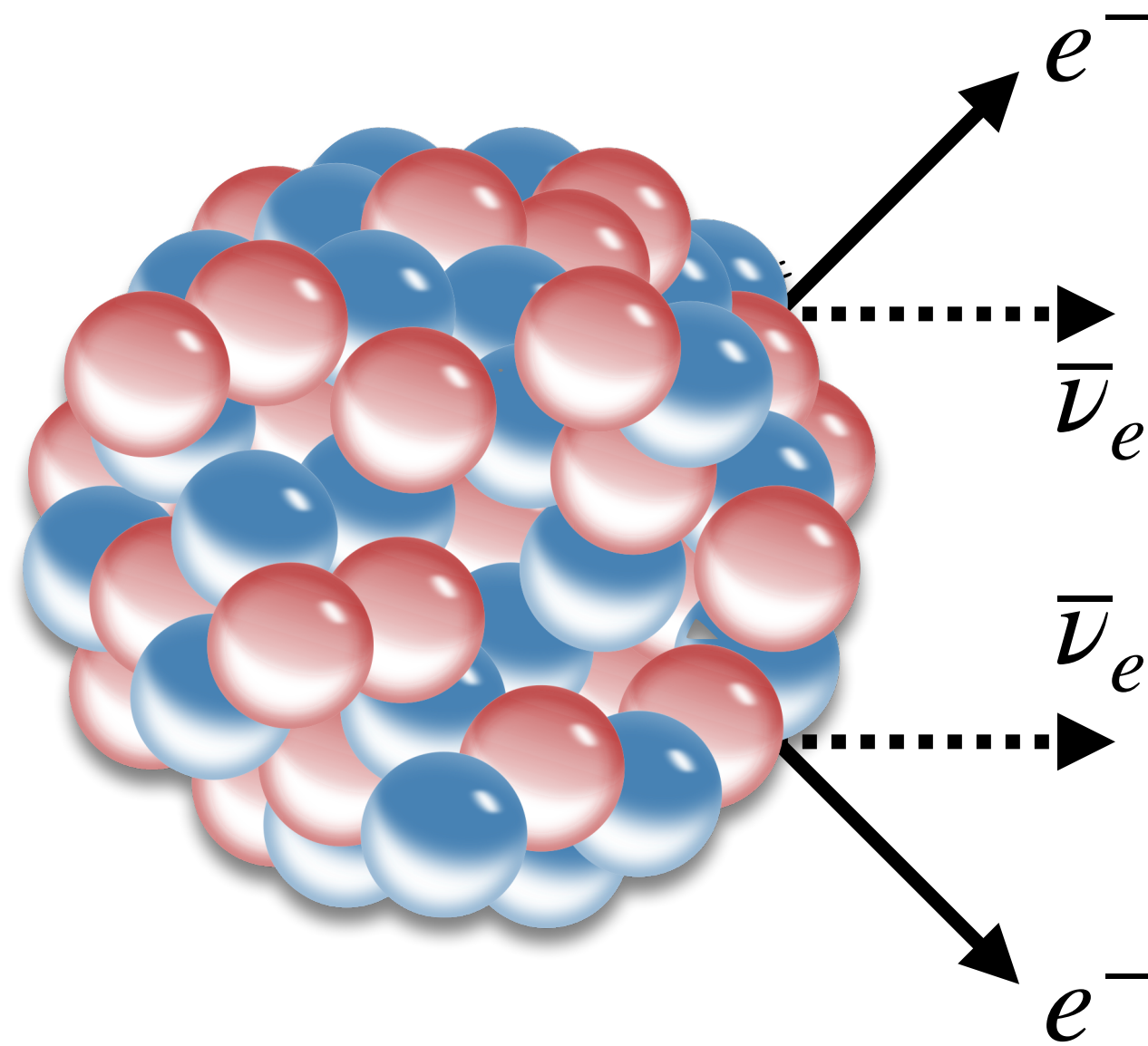
The Standard Model does not contain right-handed neutrino fields, as they'd be sterile (i.e. with no SM gauge interactions).

Therefore, neutrinos are left **massless** in the Standard Model.



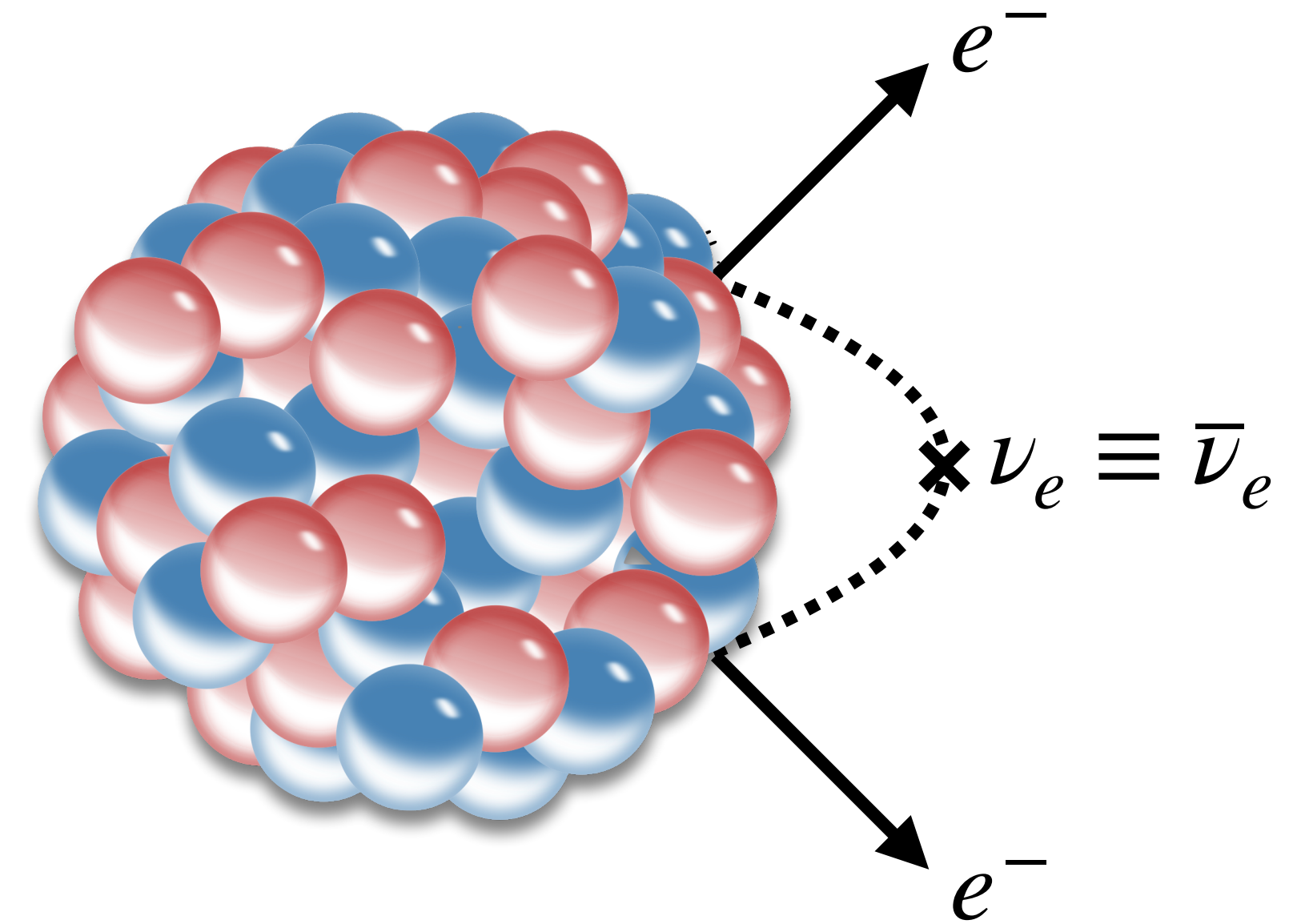
LA DESINTEGRACIÓN DOBLE BETA

9



$2\nu\beta\beta$

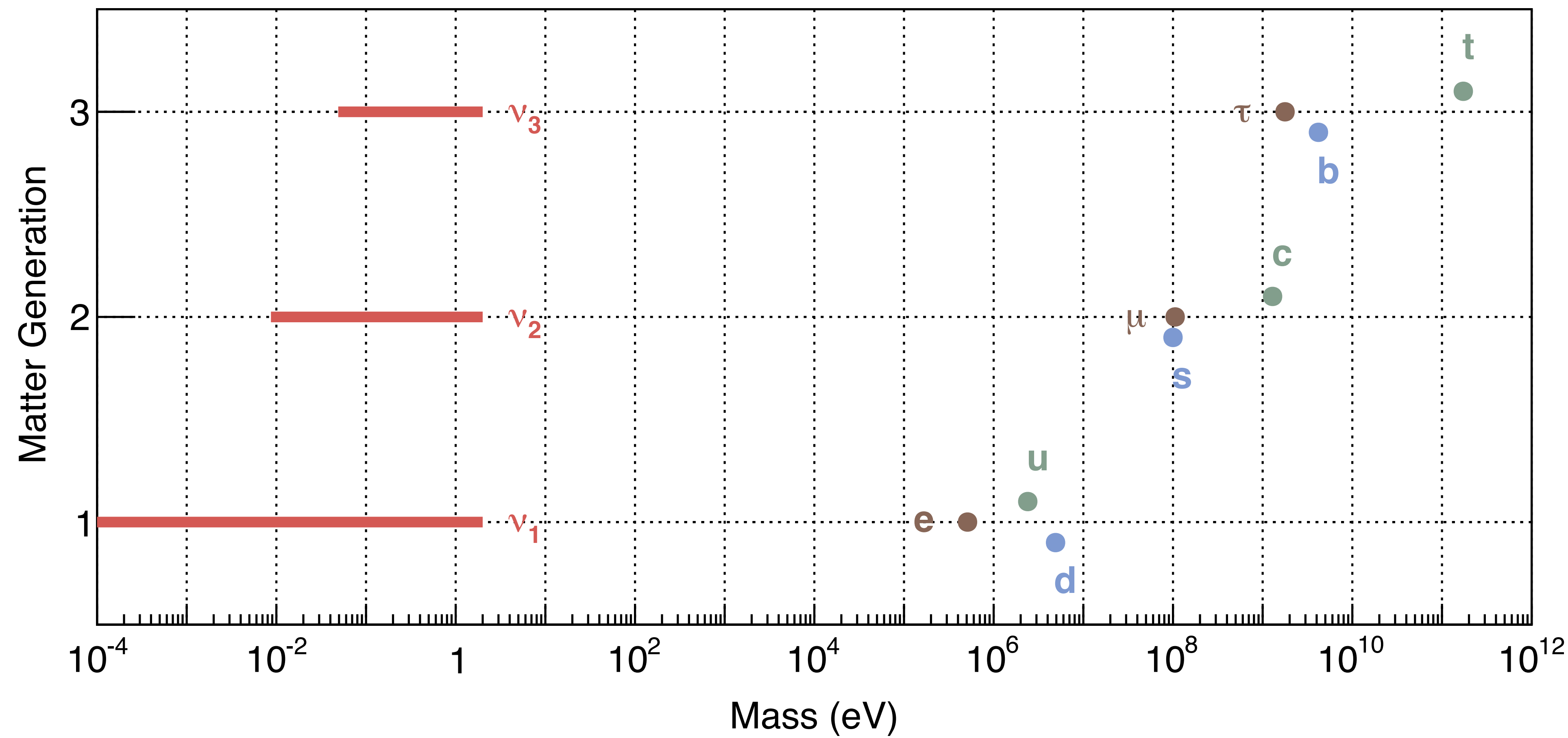
Permitido en el Modelo Estándar.
Observado en varios isótopos:
semividas del orden de 10^{18} – 10^{22} años.



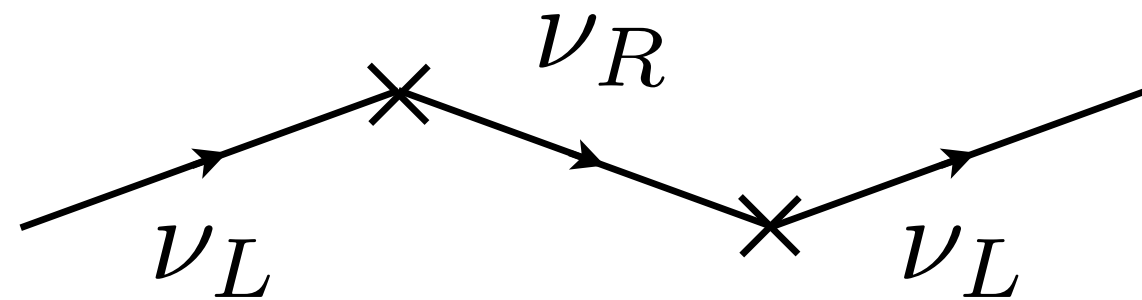
$0\nu\beta\beta$

Sólo es posible si los **neutrinos** son
partículas tipo Majorana.
Semividas de más de 10^{26} años.

LA BAJA MASA DE LOS NEUTRINOS



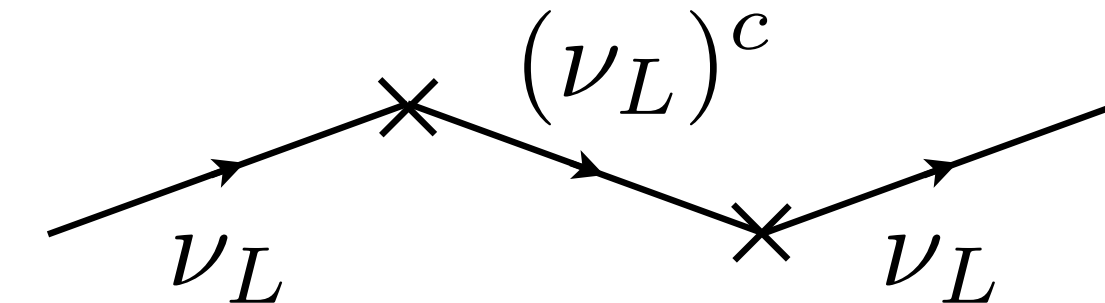
Neutrinos de Dirac



$$-\mathcal{L}_D = m \bar{\nu}_L \nu_R + \text{h.c.}$$
$$m = y v / \sqrt{2}$$

- Requiere neutrinos dextrógiros estériles.
- El número leptónico se conserva.
- El acoplamiento de Yukawa del neutrino es muy pequeño ($\sim 10^{-12}$).

Neutrinos de Majorana

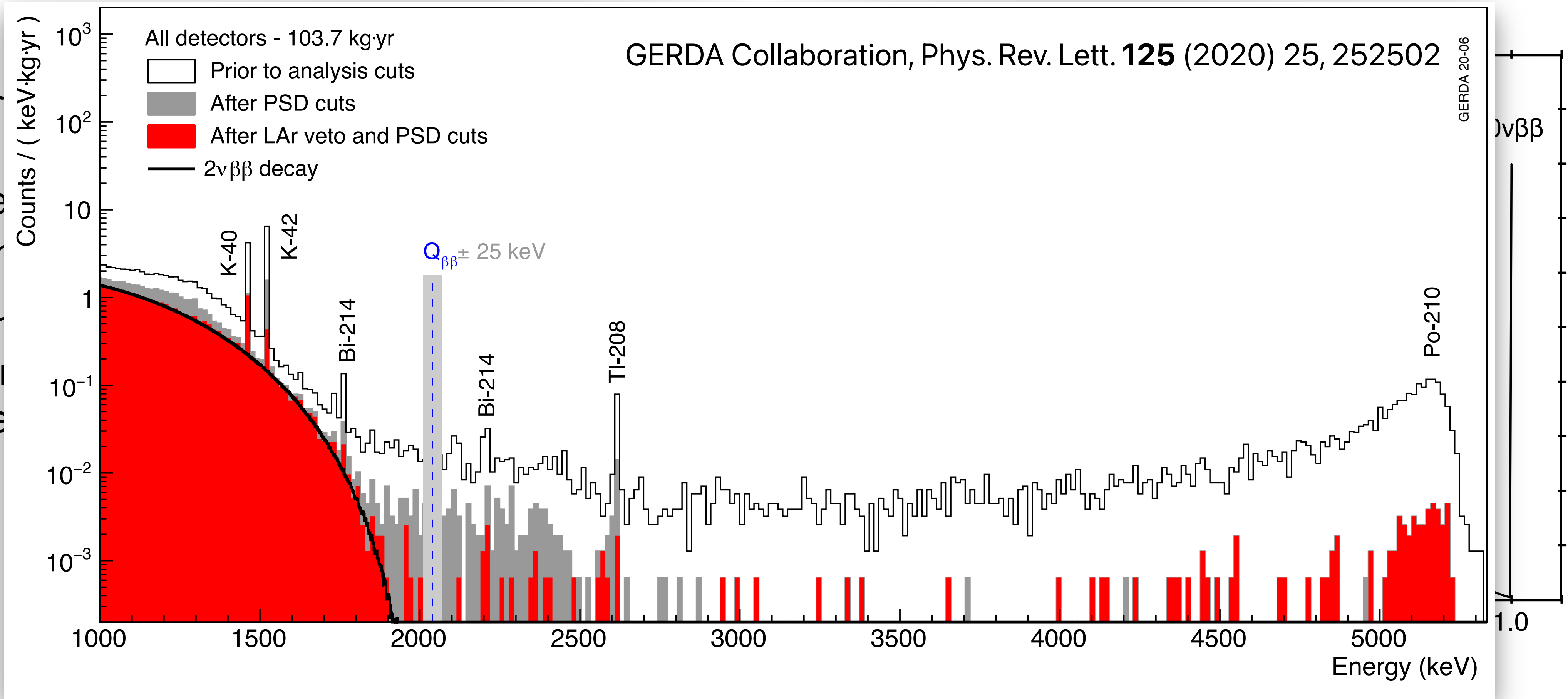


$$-\mathcal{L}_M = m \bar{\nu}_L \nu_L^c + \text{h.c.}$$
$$m = z v^2 / \Lambda$$

- Neutrinos y antineutrinos idénticos.
- Sector de Higgs extendido.
- La escala Λ suprime la masa del neutrino.

RECETA PARA UN EXPERIMENTO DE DESINTEGRACIÓN DOBLE BETA

- 1. Adqu beta
- 2. Mide distir
- 3. Cuen ocur corre

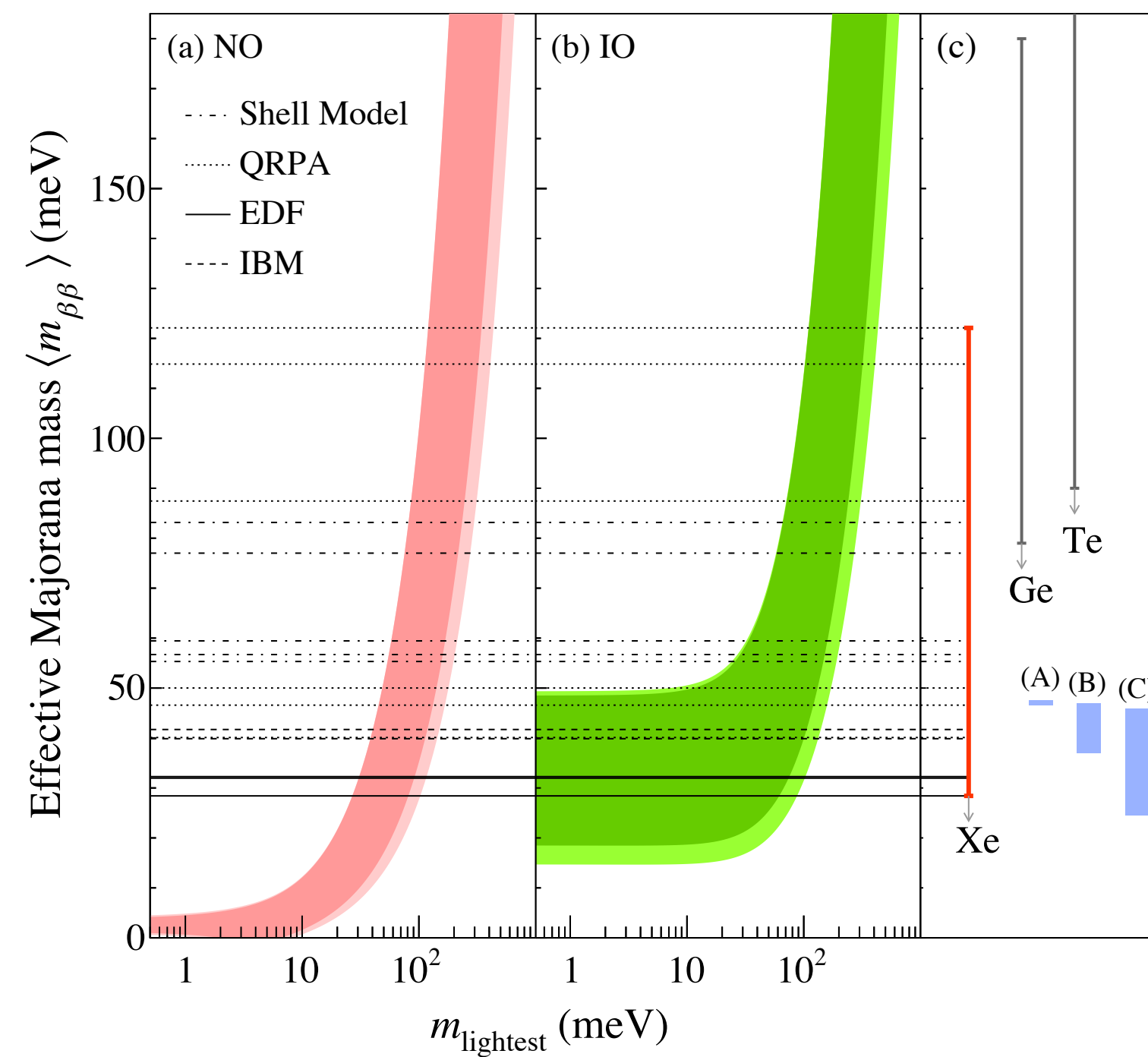


LÍMITES ACTUALES

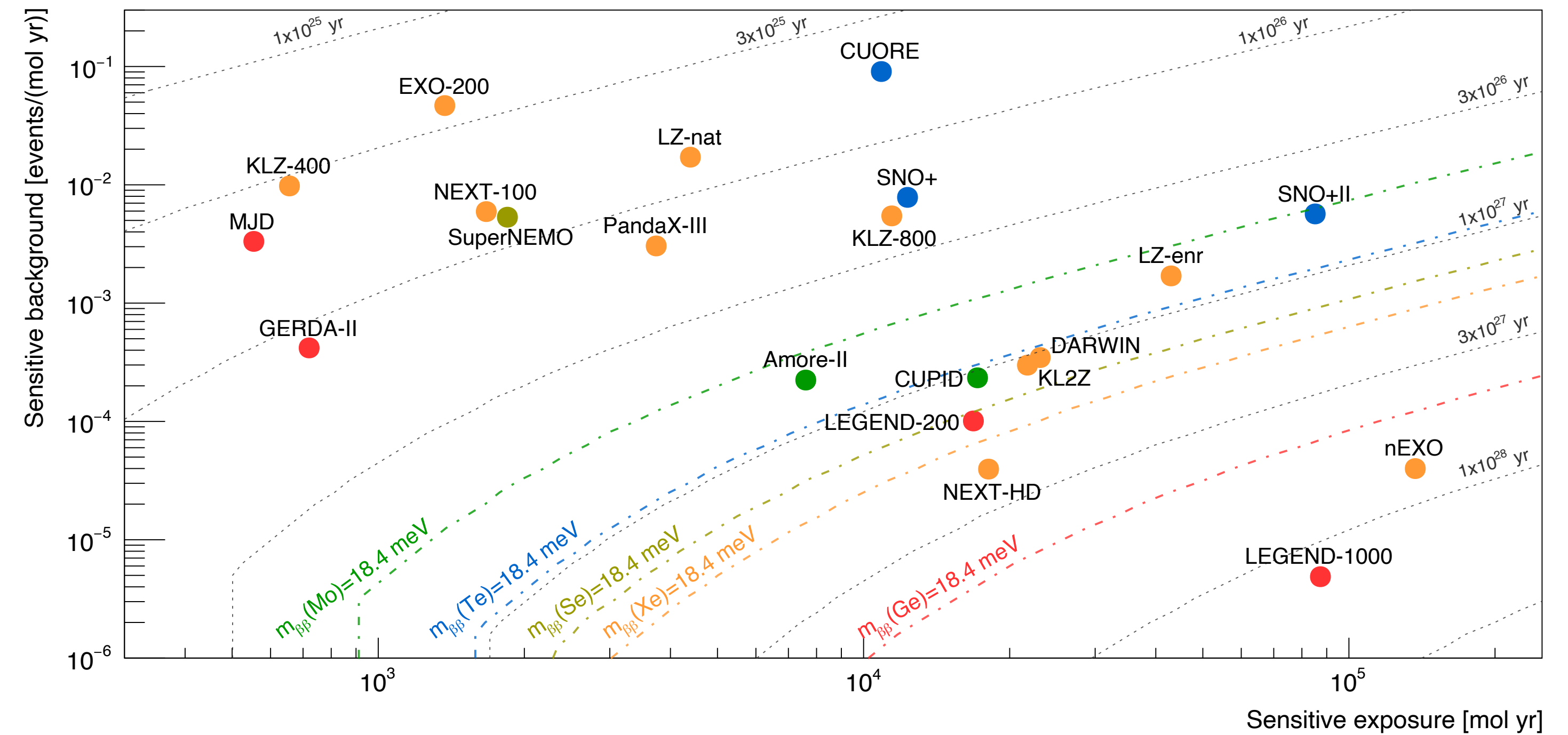
13

- **KamLAND-Zen (^{136}Xe):** $T_{1/2} > 3.8 \times 10^{26}$ años (90% CL) $\rightarrow m_{\beta\beta} < 28\text{--}122$ meV
- **GERDA (^{76}Ge):** $T_{1/2} > 1.8 \times 10^{26}$ años (90% CL) $\rightarrow m_{\beta\beta} < 79\text{--}180$ meV

arXiv:2406.11438



Rev. Mod. Phys. **95** (2023) 2, 025002



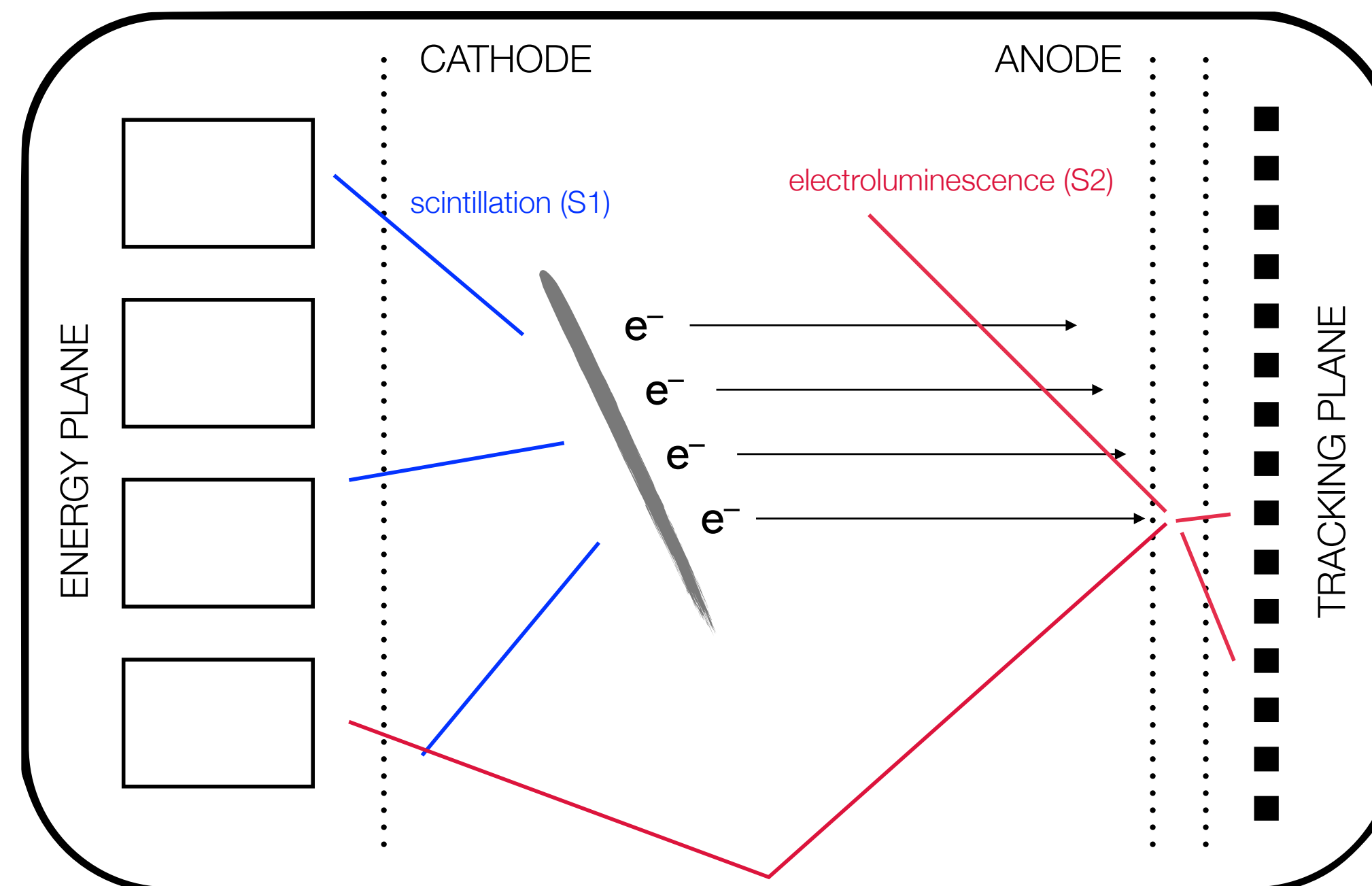
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2 \quad m_{\beta\beta} = \sum_i |U_e^2 i| m_i$$

EL EXPERIMENTO NEXT

14

Búsqueda de la desintegración $0\nu\beta\beta$ del ^{136}Xe con cámaras de proyección temporal (**TPC**) de gas **xenón a presión**.

- ▶ Amplificación mediante **electroluminiscencia** (EL).
- ▶ **Señales ópticas** detectadas con tubos fotomultiplicadores (PMT) y fotomultiplicadores de silicio (SiPM).
- ▶ **Excelente resolución energética**: $<1\%$ FWHM a la energía de la desintegración (~ 2.5 MeV).
- ▶ **Reconstrucción de trazas** para la identificación de señal (dos electrones) y ruido (un electrón).

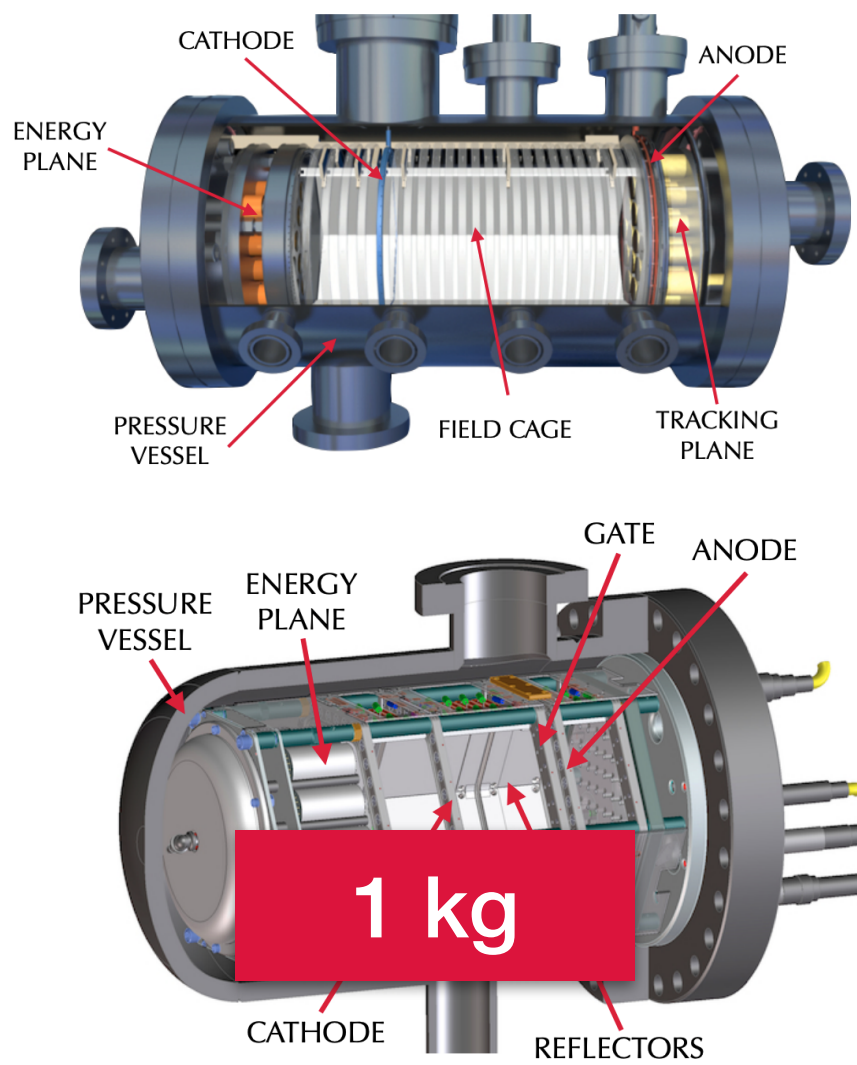


EL EXPERIMENTO NEXT

Prototipos

(2010–2014)

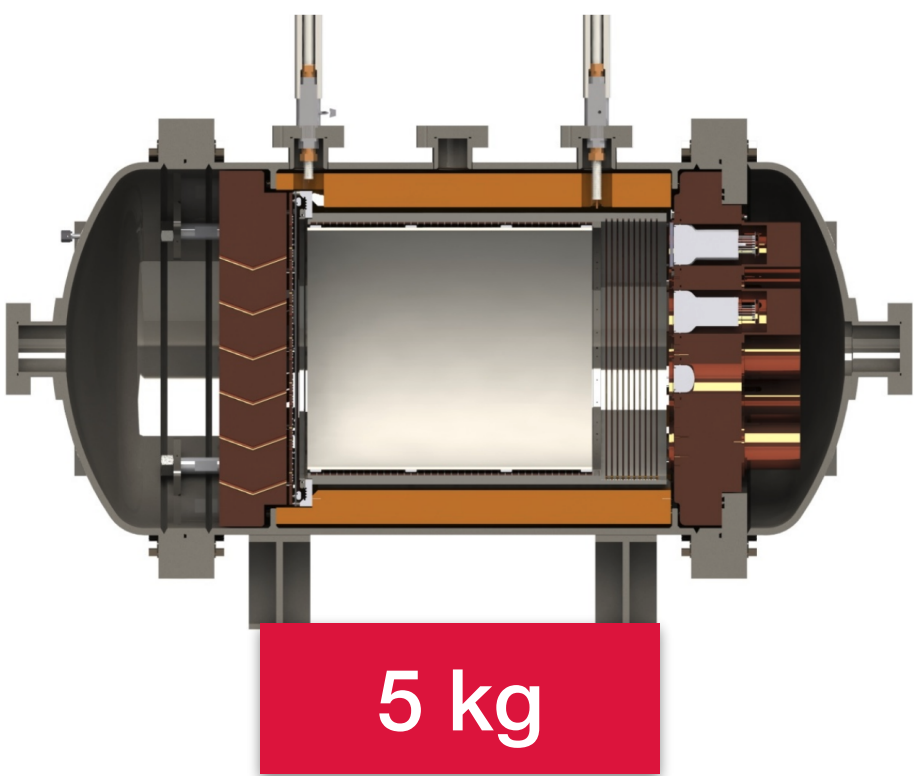
Demonstradores tecnológicos



NEXT-White

(2015–2021)

Verificación del modelo de fondo y medida del $2\nu\beta\beta$



NEXT-100

(2024–2031)

Búsqueda del $0\nu\beta\beta$ (10^{26} años) y demostración tecnológica



NEXT-HD/BOLD

(2032–20...)

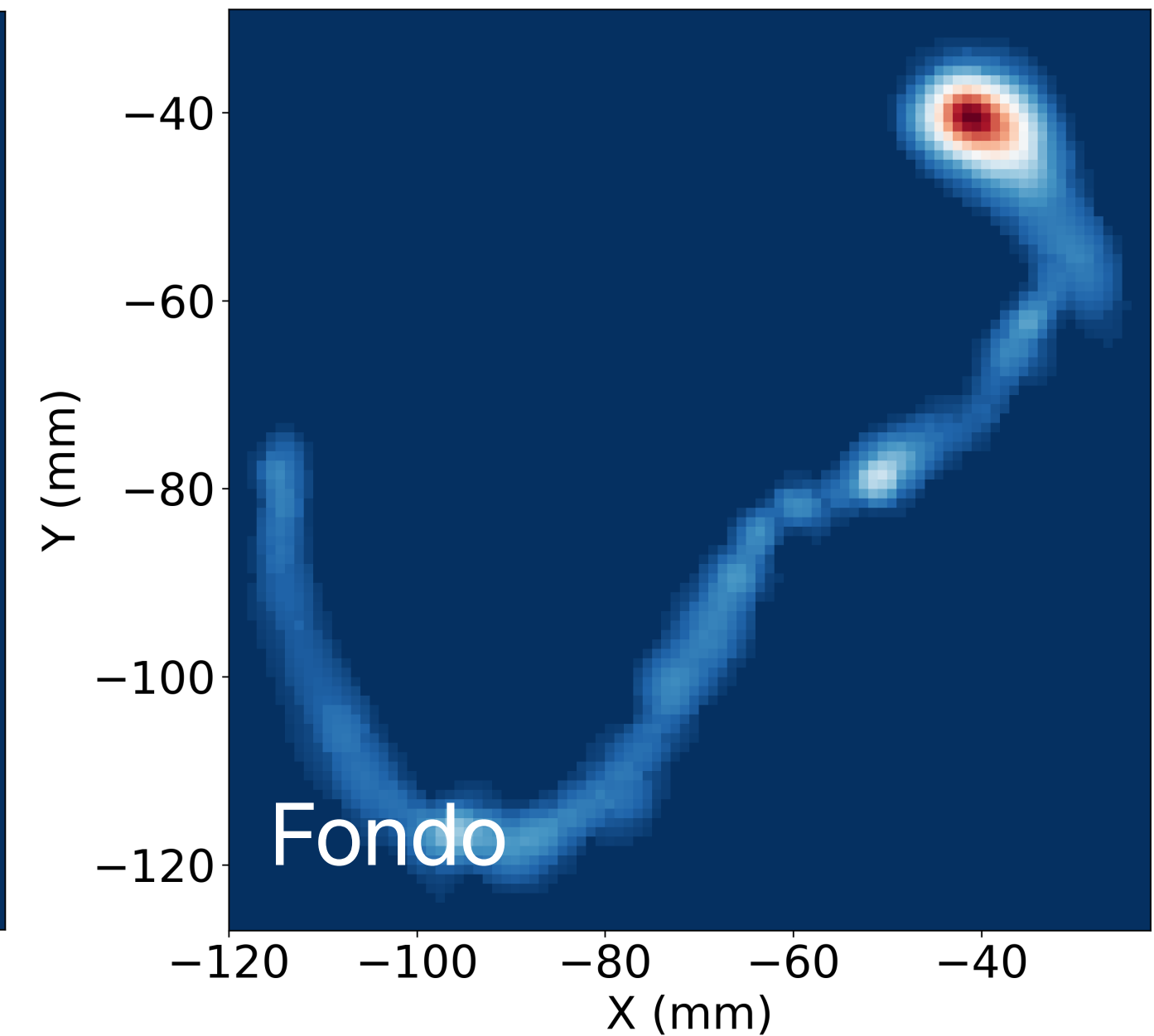
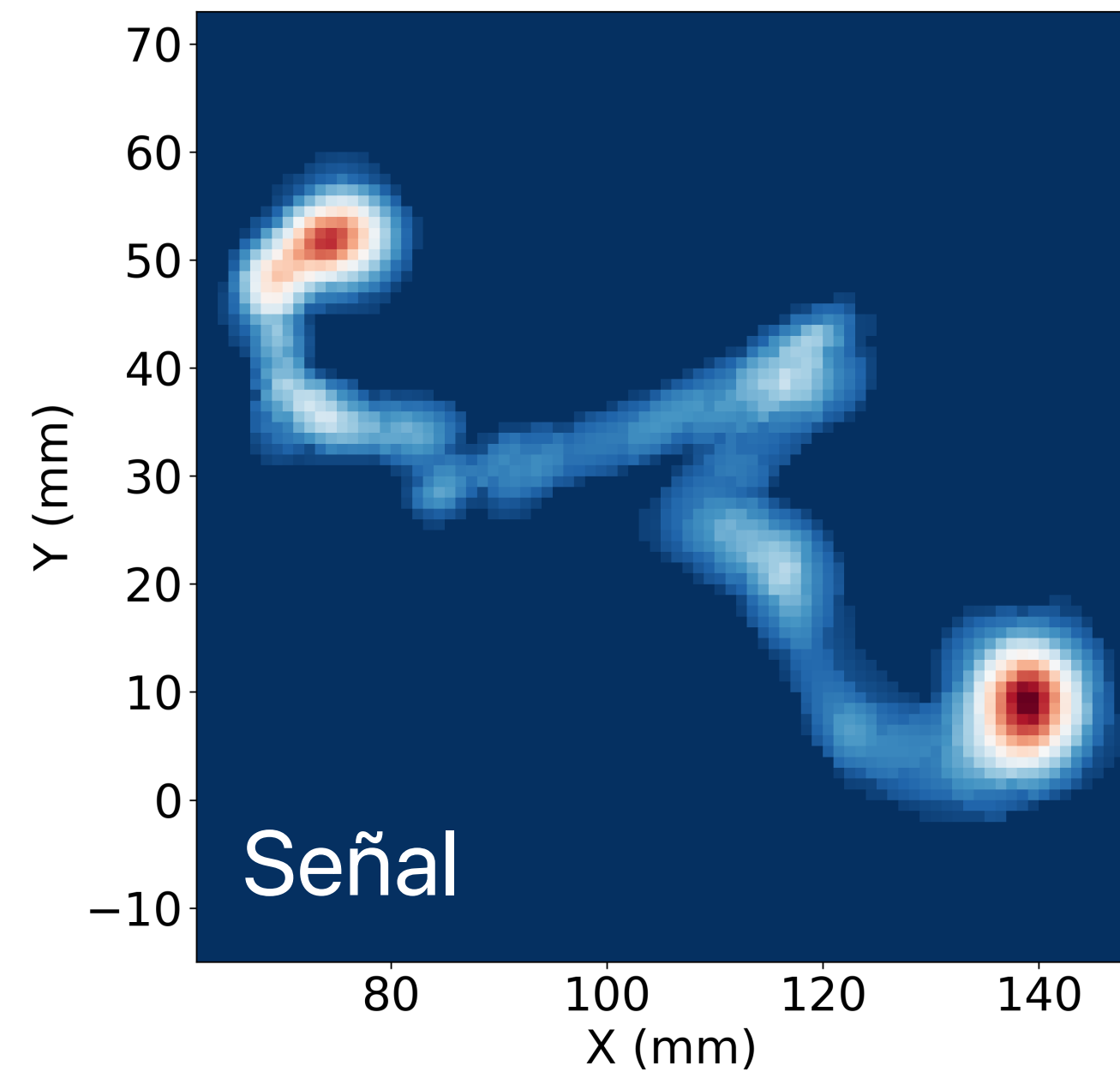
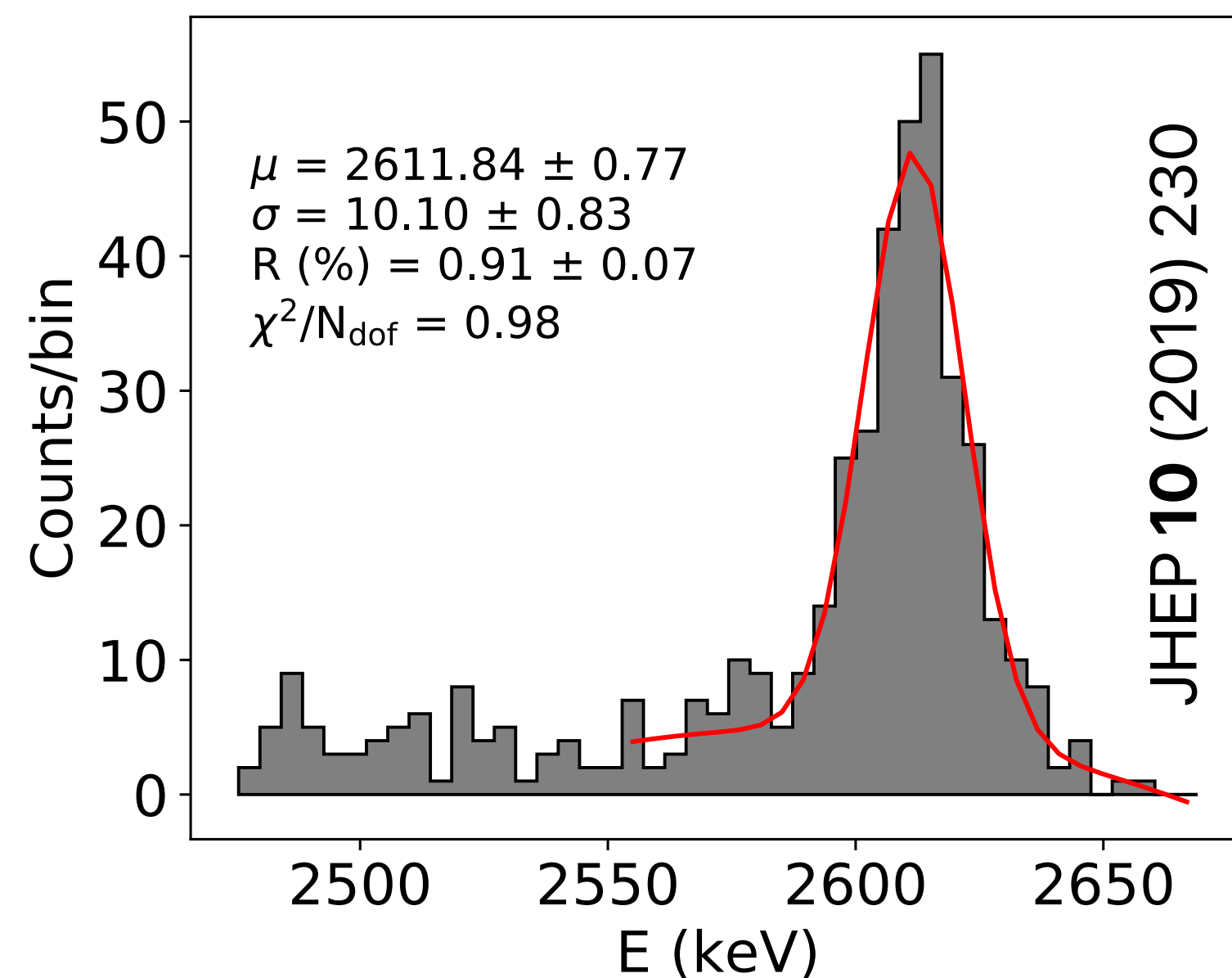
Búsqueda del $0\nu\beta\beta$ (10^{28} años)



EL EXPERIMENTO NEXT: RESULTADOS (1)

16

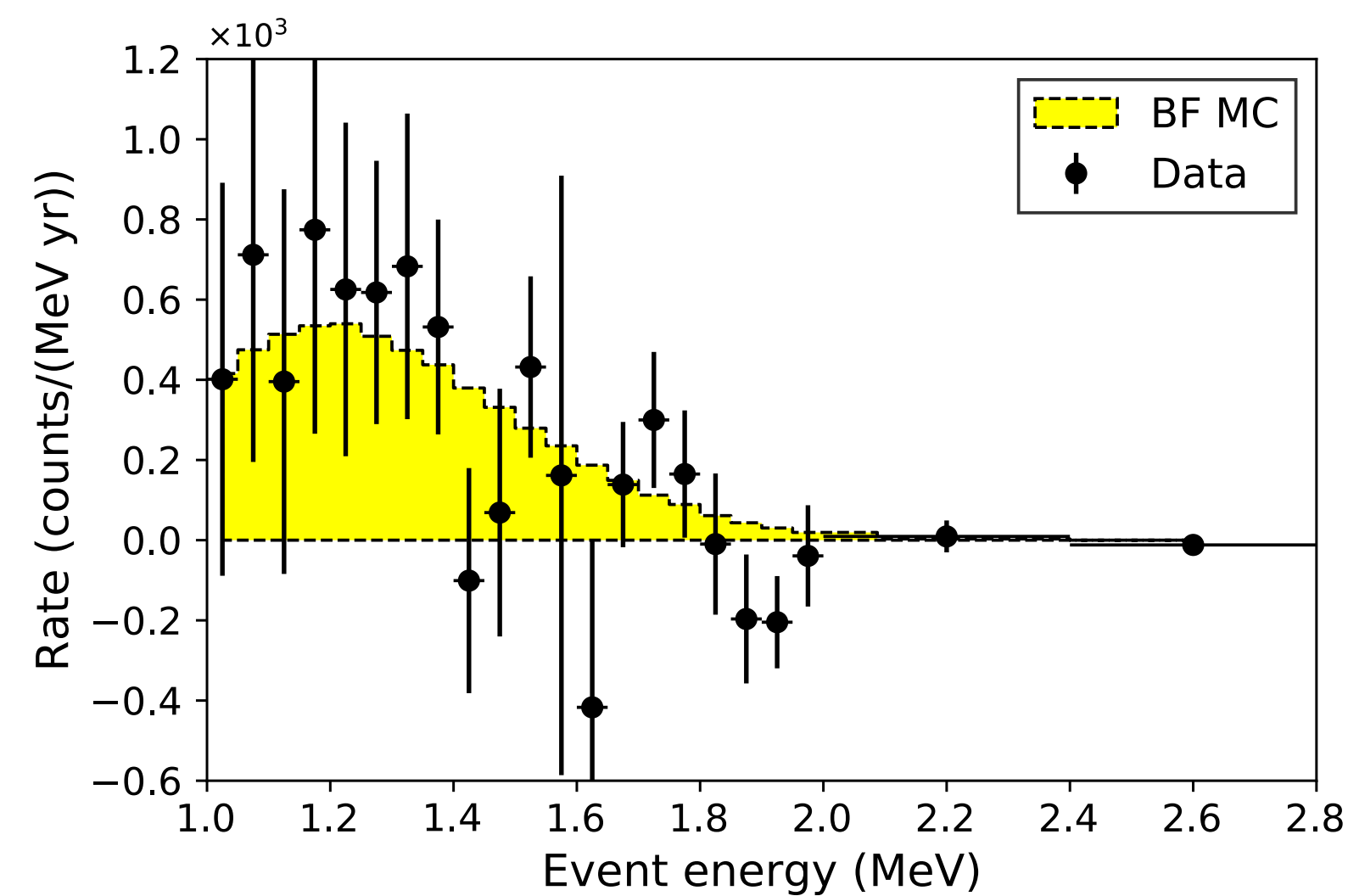
- **Resolución energética** (medida a diferentes energías) extrapolable a **<1% FWHM a 2.5 MeV**.
- **Reconstrucción de trazas eficaz** para distinguir eventos con 1 o 2 electrones.



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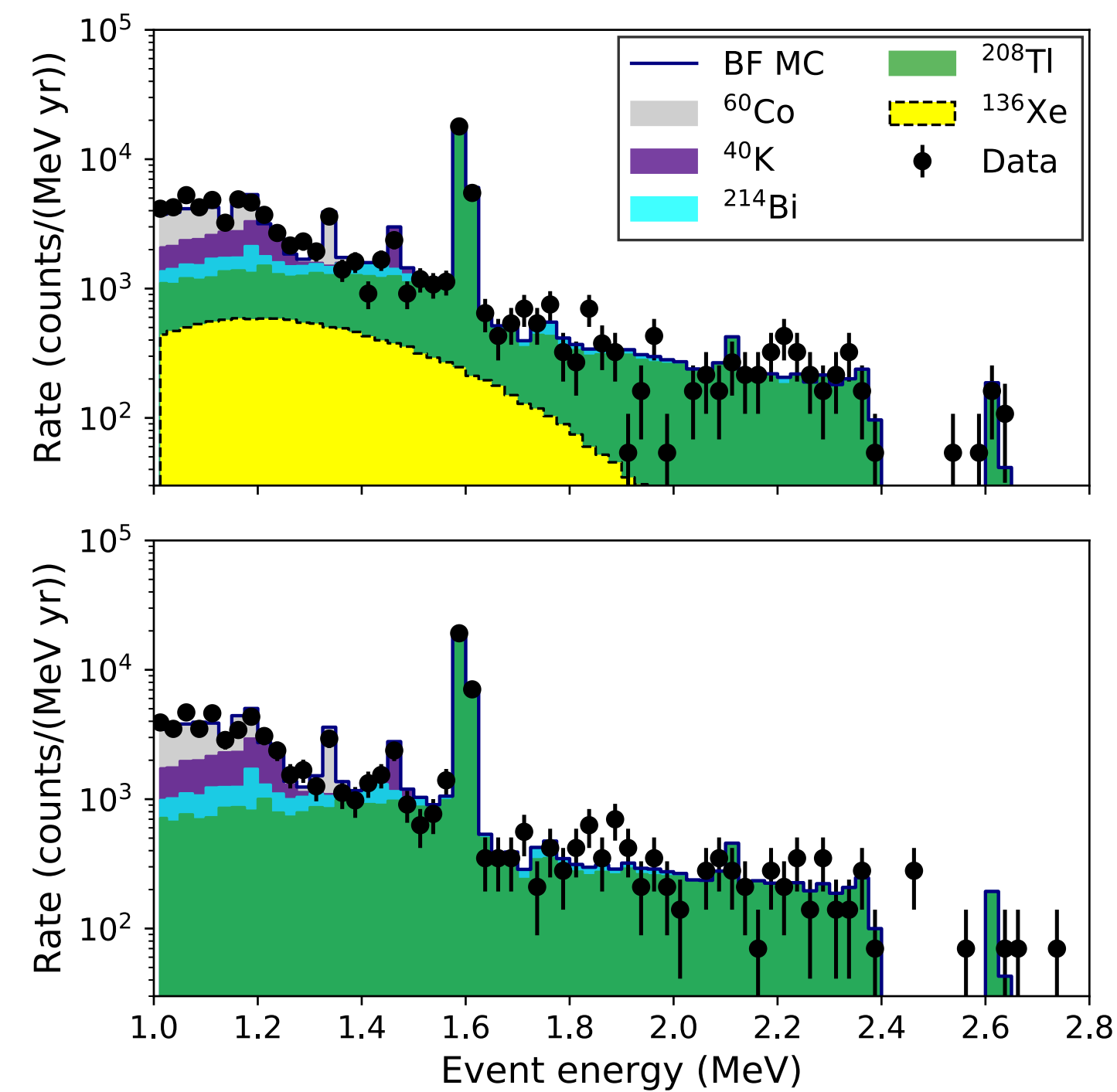
EL EXPERIMENTO NEXT: RESULTADOS (2)

- **Medida de la semivida de la desintegración $2\nu\beta\beta$ del ^{136}Xe en NEXT-White usando dos métodos de análisis diferentes:**
 - Sustracción de los espectros medidos con xenón enriquecido y con xenón empobrecido en ^{136}Xe .
 - Ajuste de los datos al modelo de fondo del experimento.



$$T_{1/2} = 2.34^{+0.80}_{-0.46} \text{ (stat)} \text{ } ^{+0.30}_{-0.17} \text{ (sys)} \times 10^{21} \text{ yr}$$

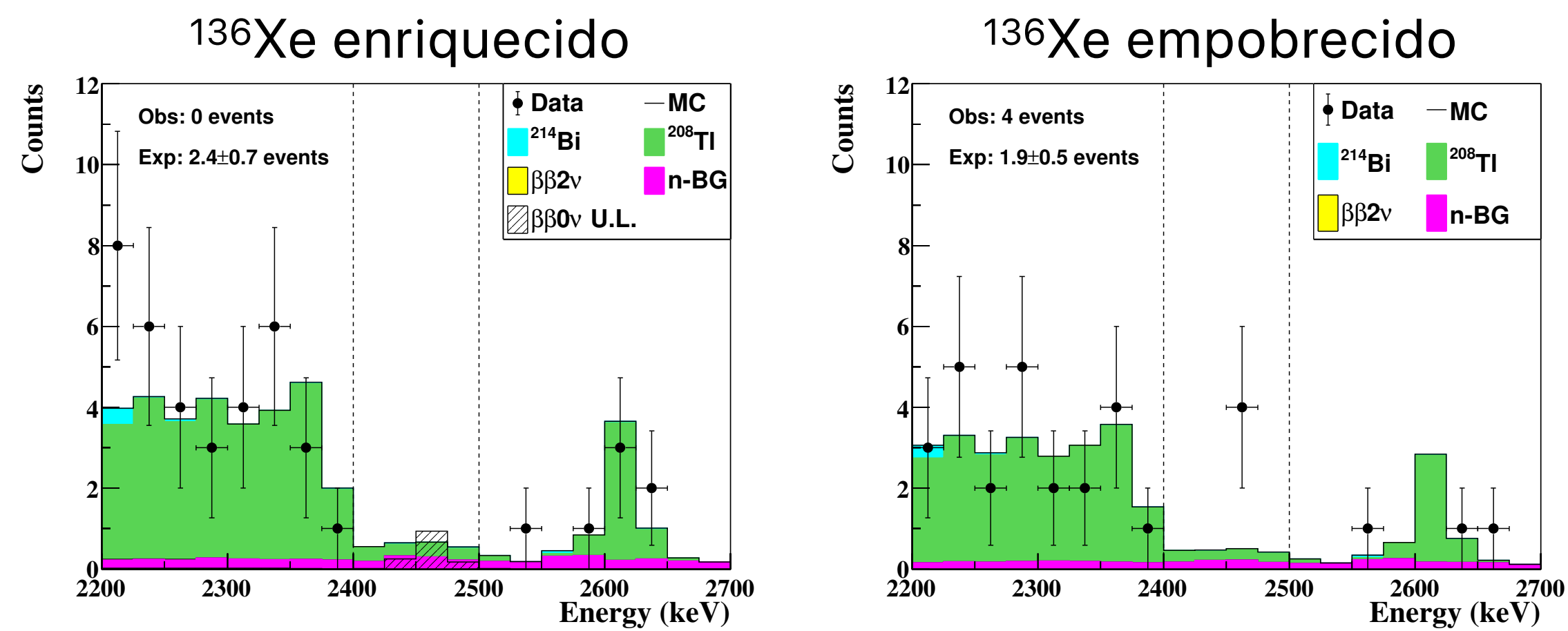
Phys. Rev. C **105** (2022) 5, 055501



Phys. Rev. C **105** (2022) 5, 055501

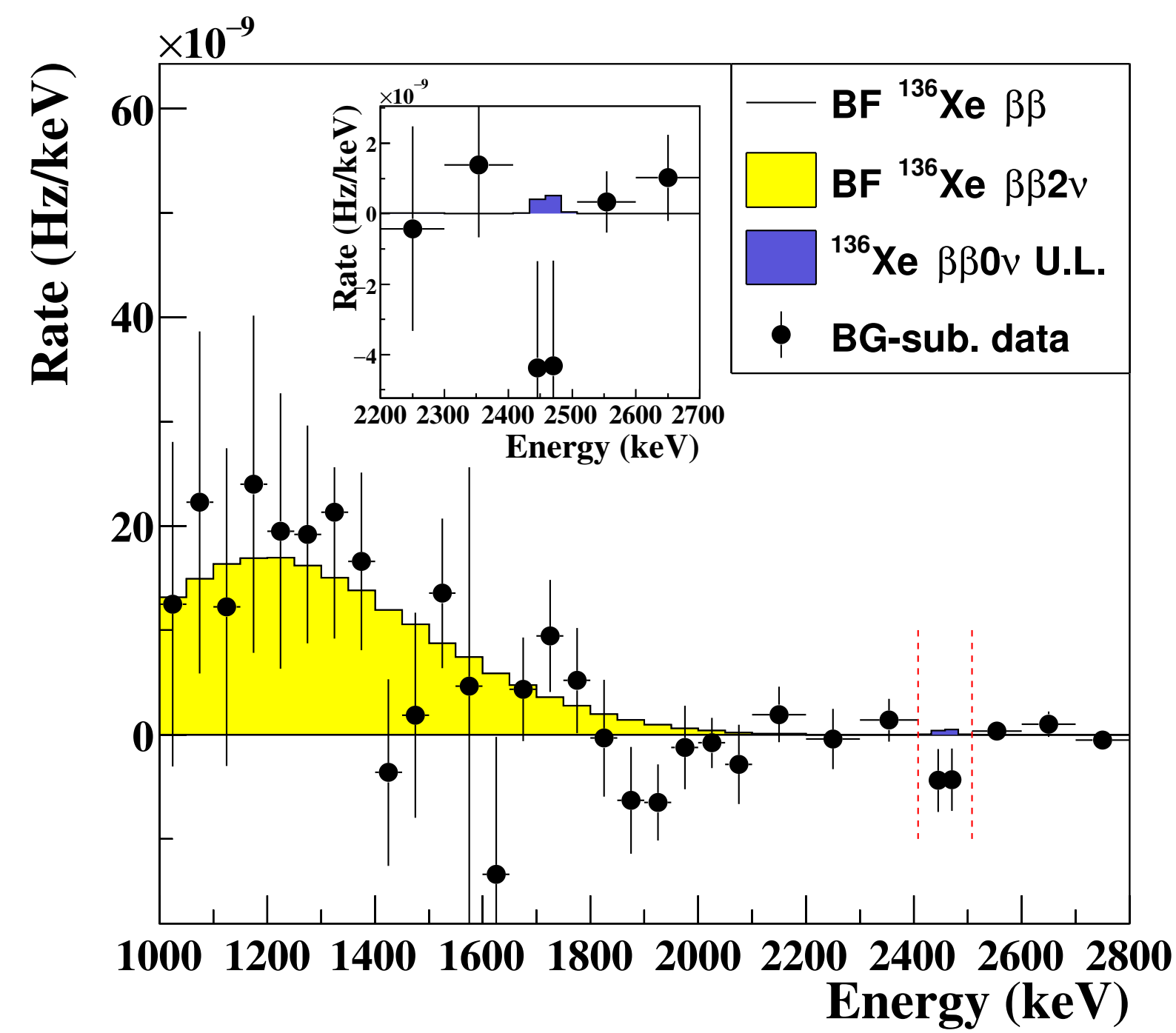
EL EXPERIMENTO NEXT: RESULTADOS (y 3)

- Búsqueda de la desintegración $0\nu\beta\beta$ del ^{136}Xe en NEXT-White.
 - Dada la baja exposición, el resultado no es competitivo con los mejores límites actuales, pero demuestra las capacidades de búsqueda de la tecnología.



Ajuste al modelo de fondo: $T_{1/2}^{0\nu} > 5.5 \times 10^{23} \text{ yr}$

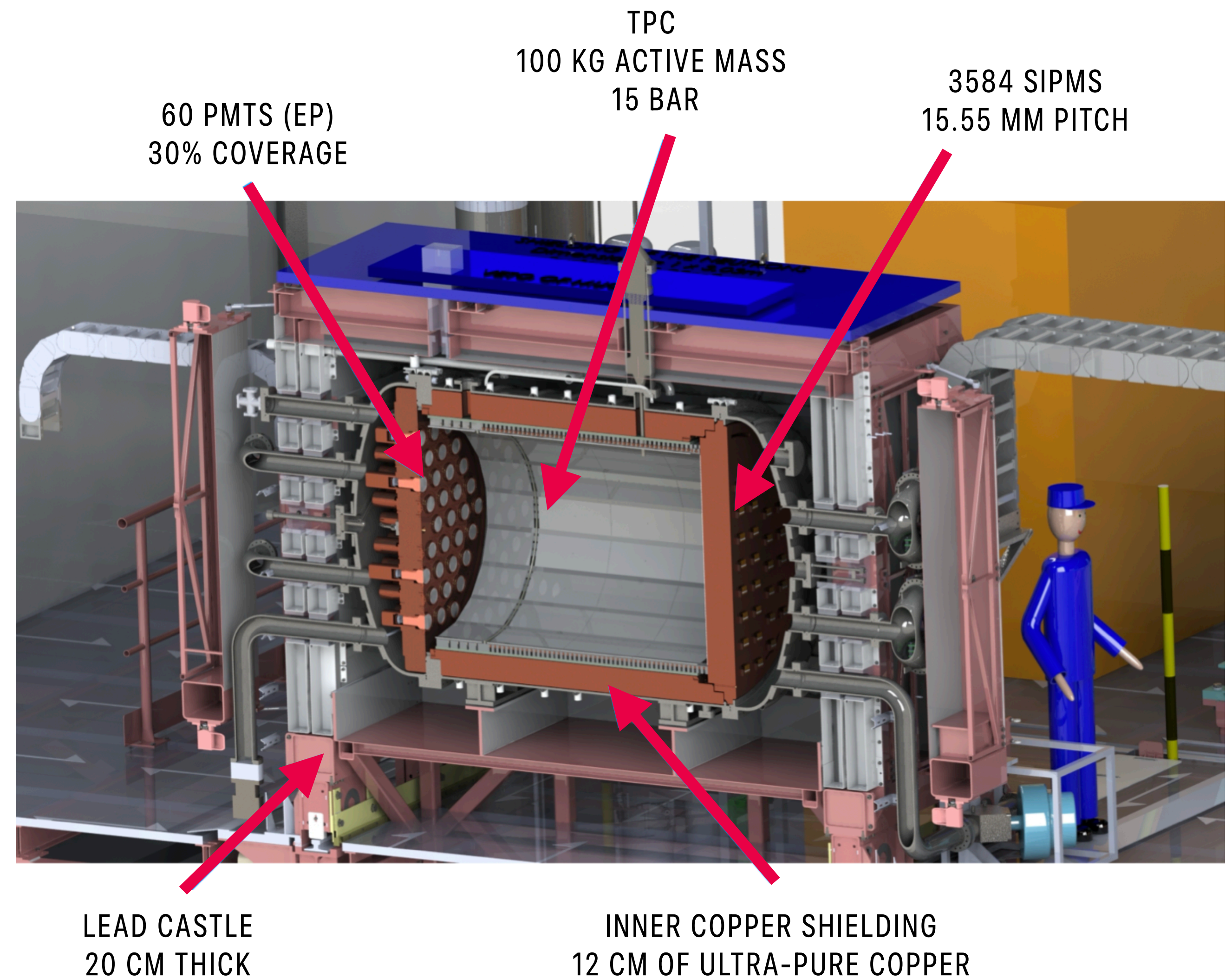
Sustracción de fondo: $T_{1/2}^{0\nu} > 1.3 \times 10^{24} \text{ yr}$



NEXT-100

19

- **Operando** en el Laboratorio Subterráneo de Canfranc (LSC) desde la **primavera de 2024**.
- **Objetivos:**
 - ▶ Mejorar la **resolución energética** y **separación de señal y ruido** obtenidas con NEXT-White.
 - ▶ **Tasa de ruido** inferior a 1 cuenta/año.
 - ▶ **Preparar** el camino tecnológico hacia la **escala de la tonelada** con actualizaciones de los sistemas de fotodetección (nueva electrónica para SiPMs y barril de fibras centelladoras).

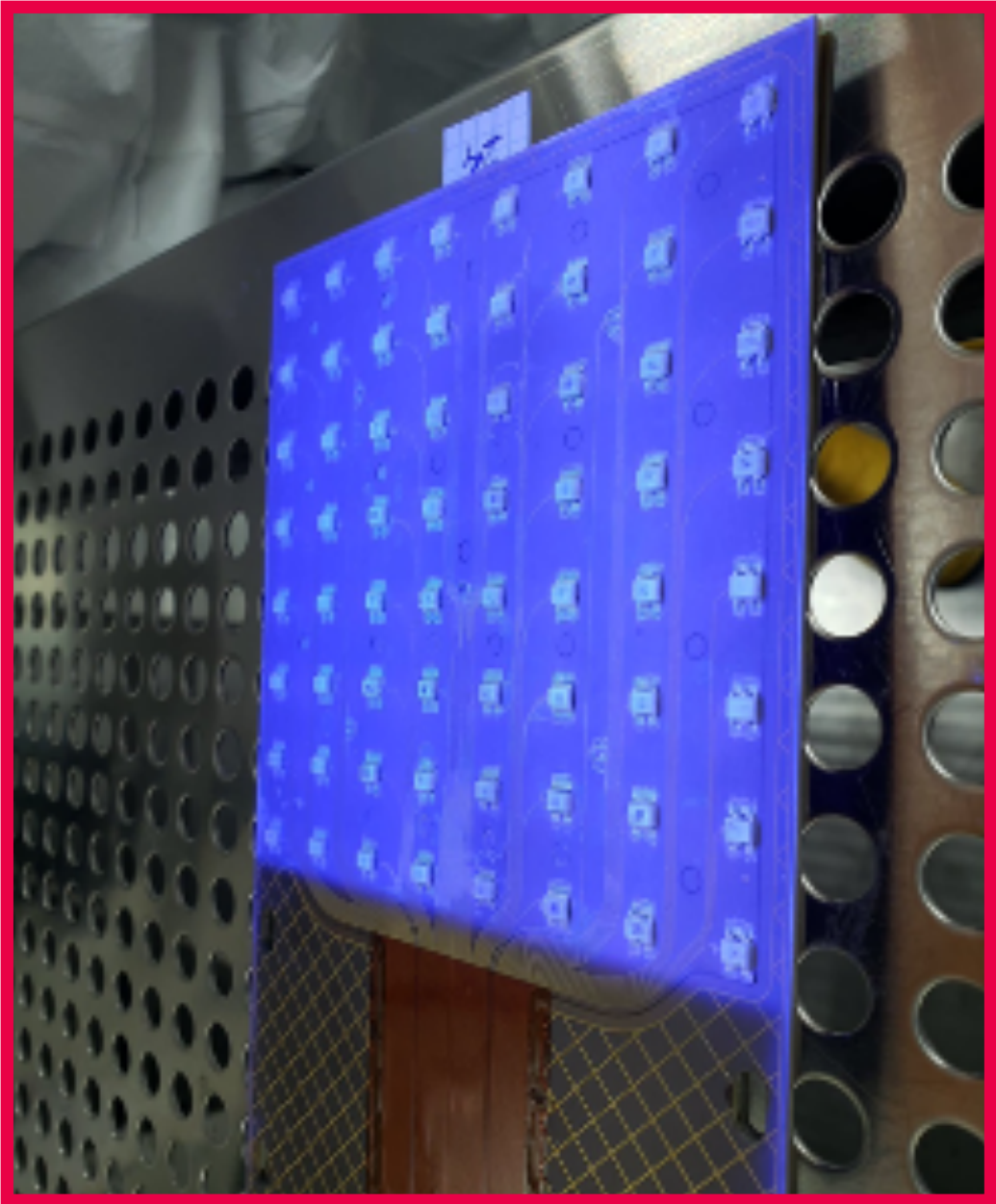
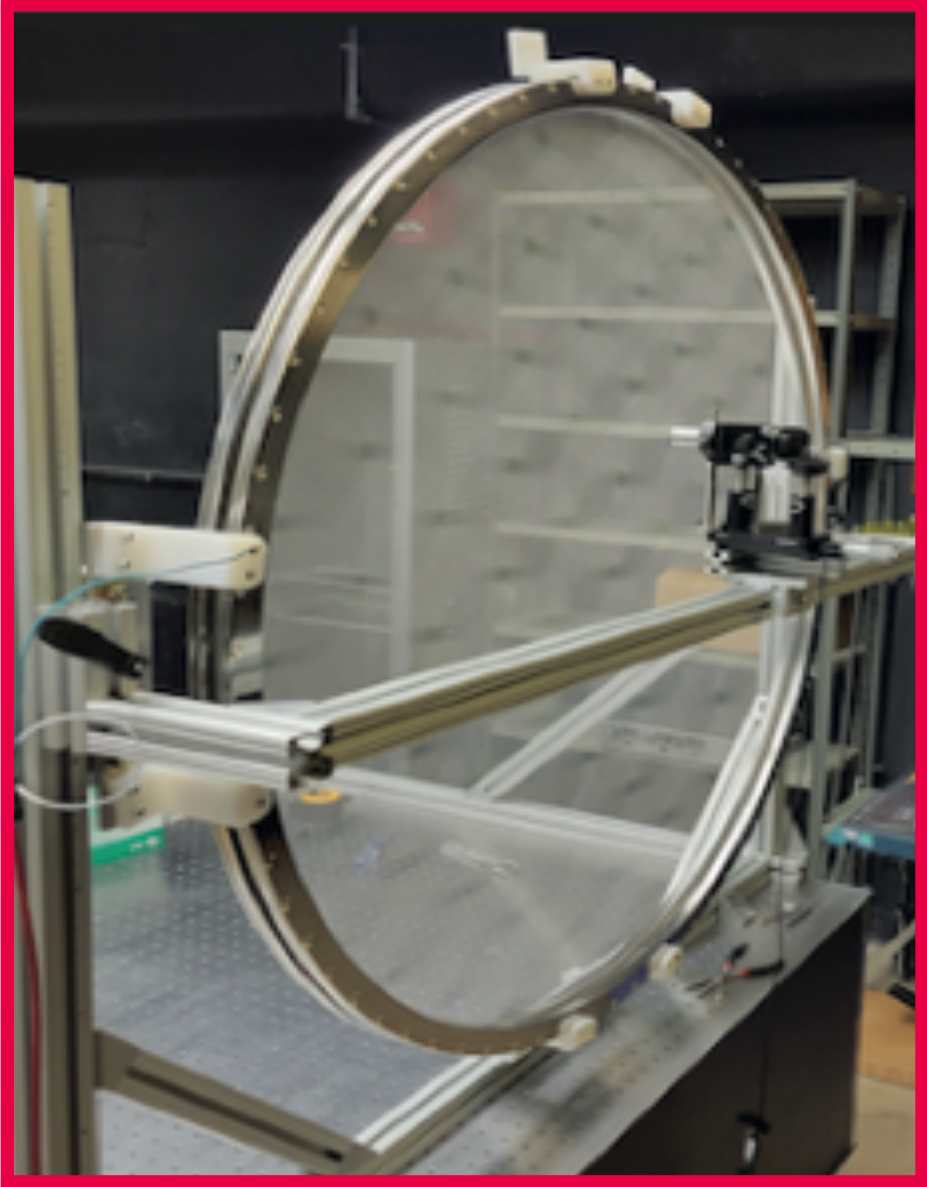
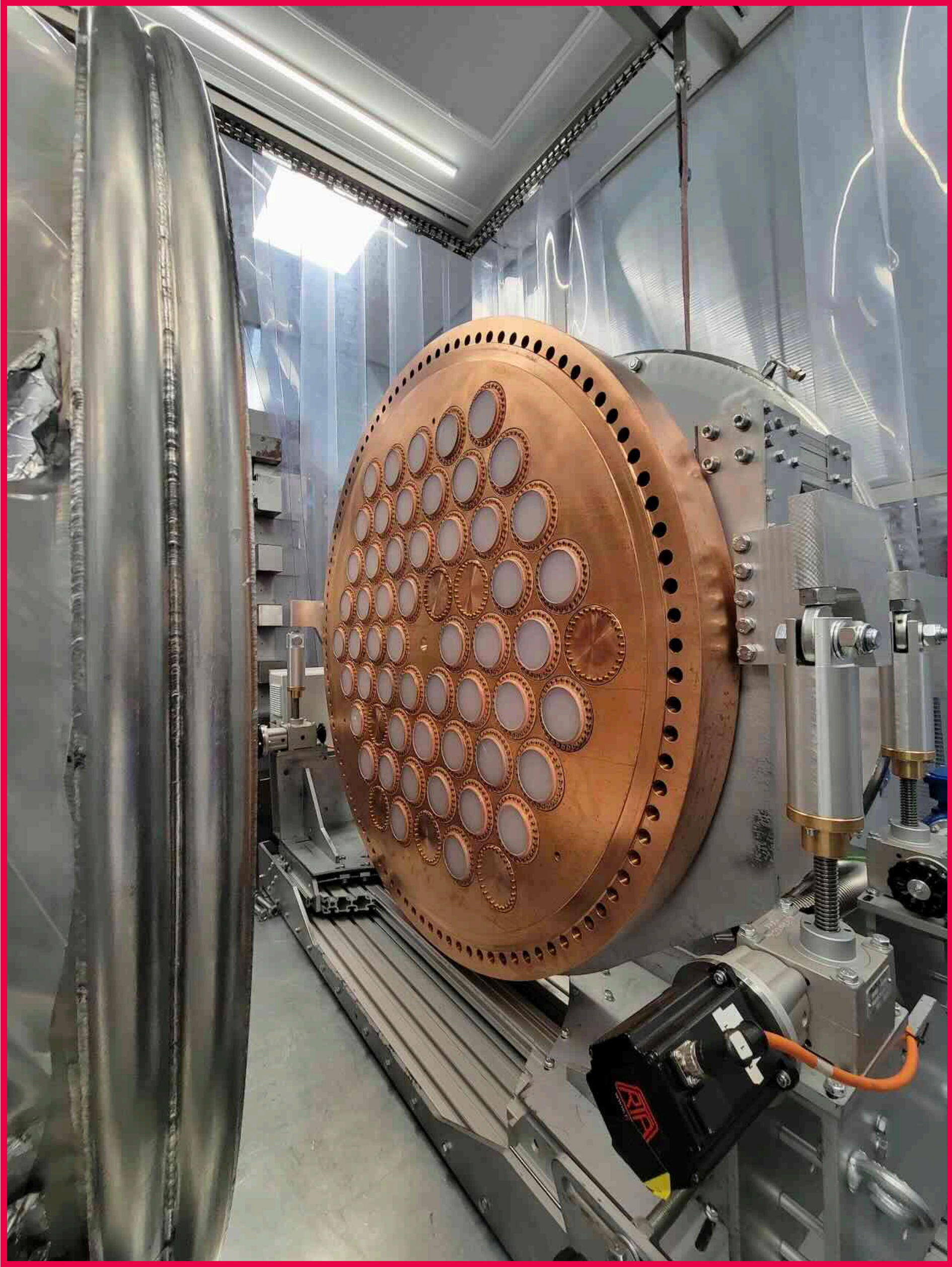
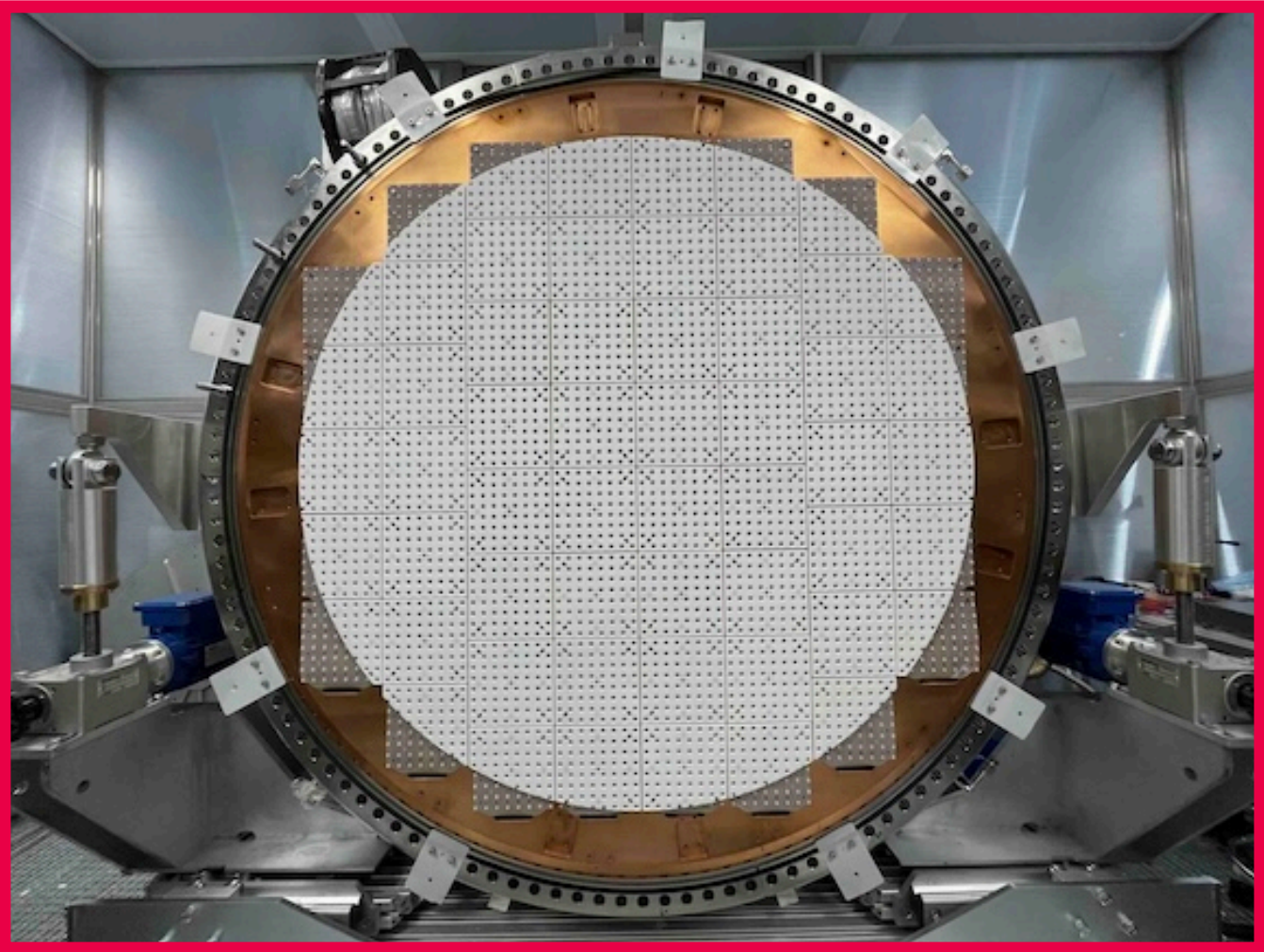
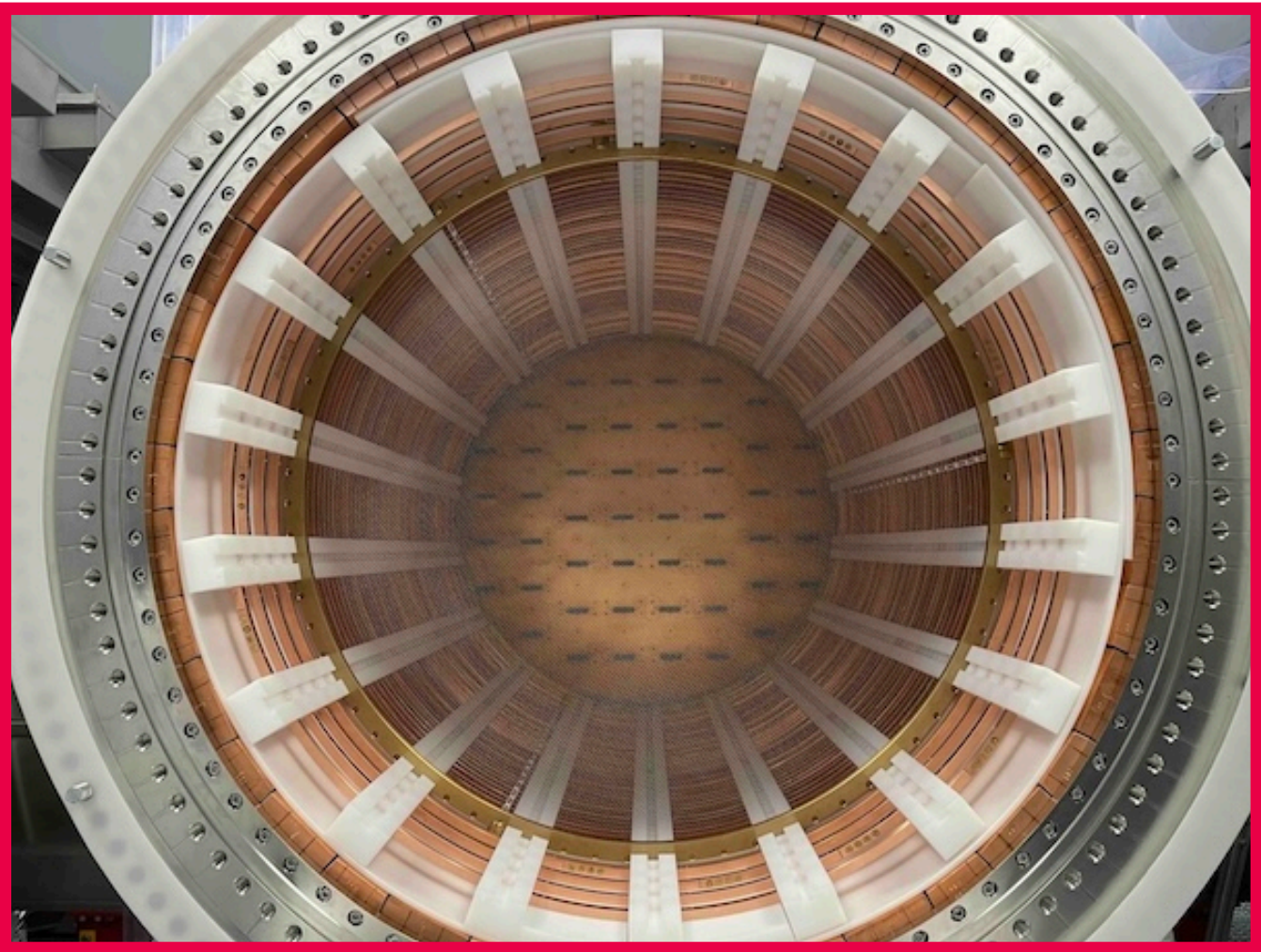


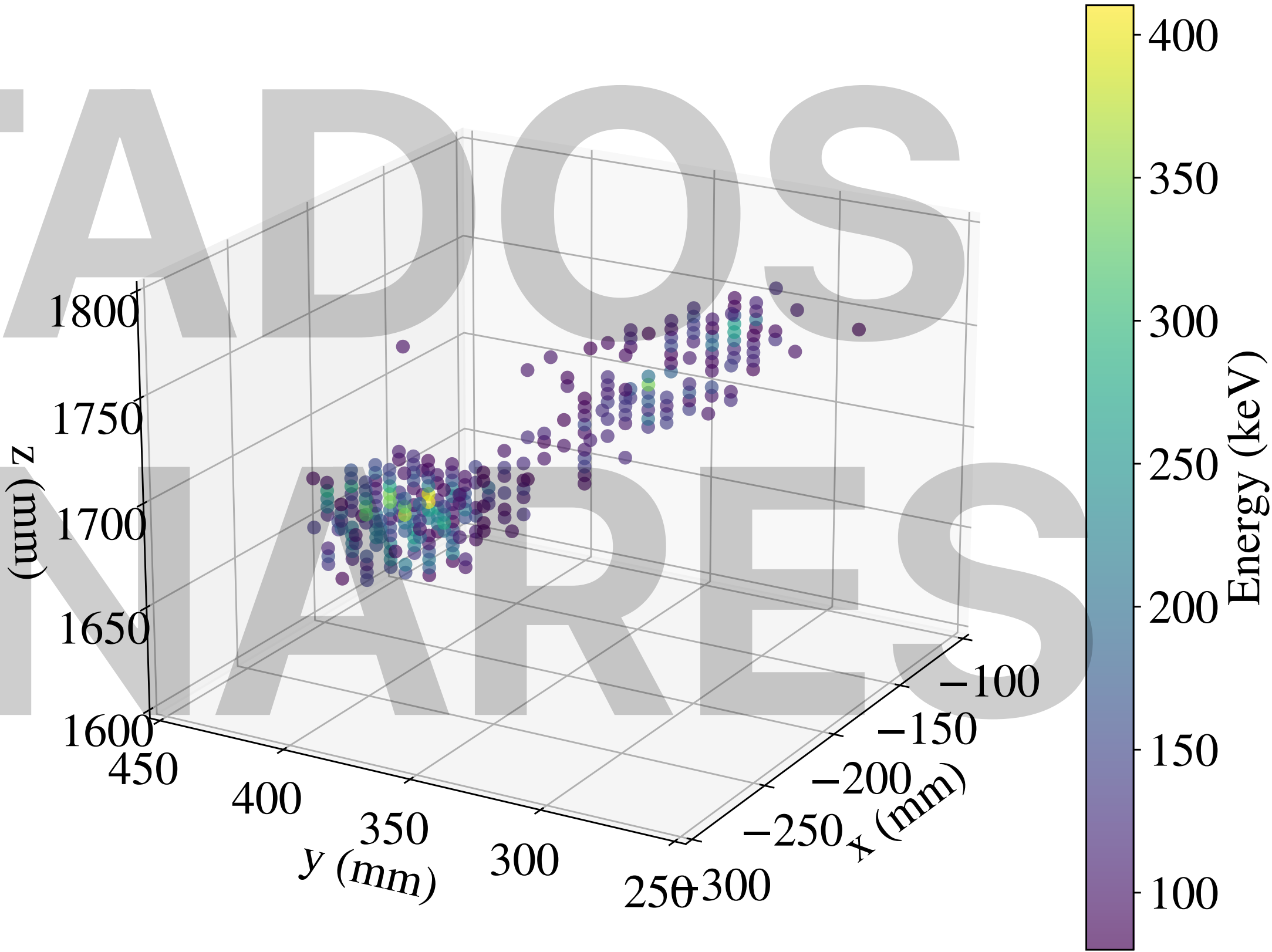
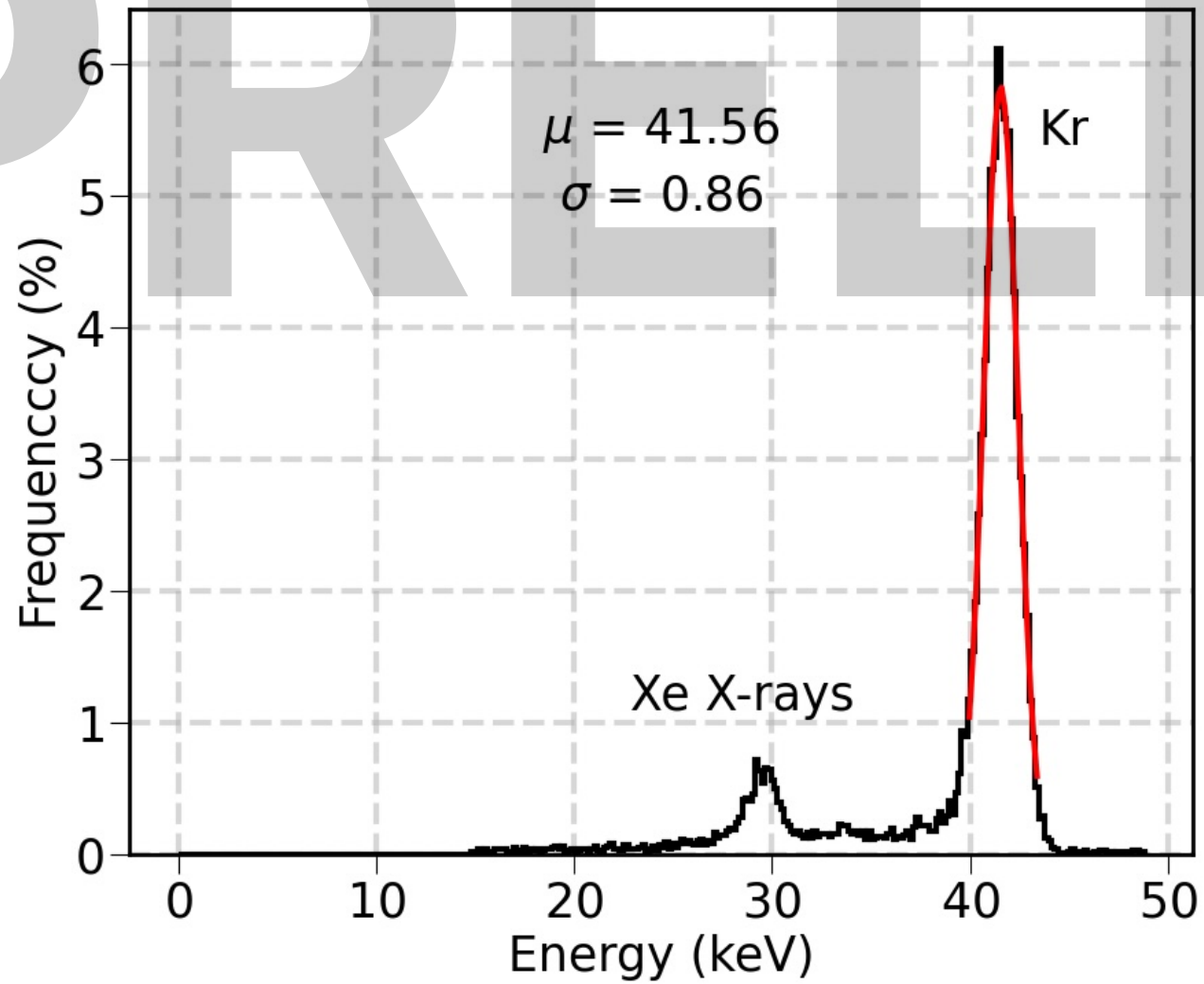
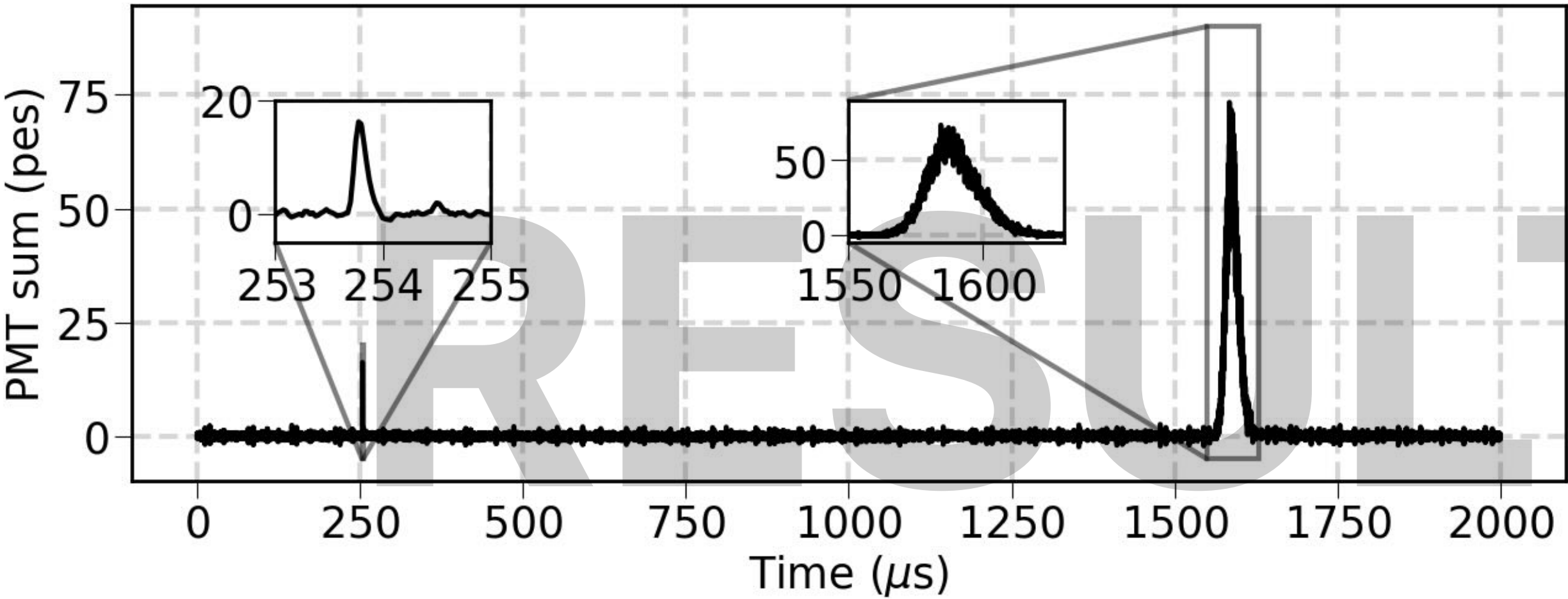
NEXT-100

20



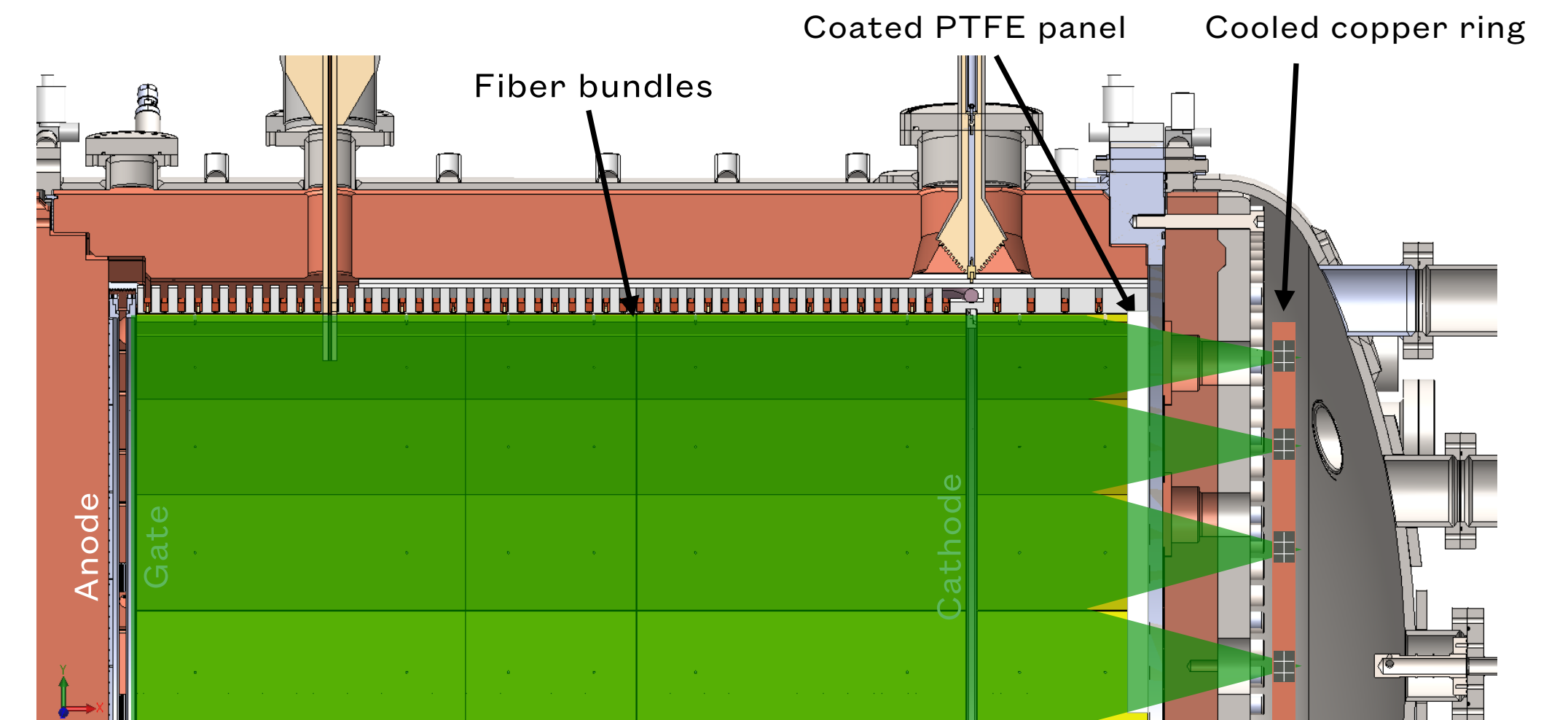
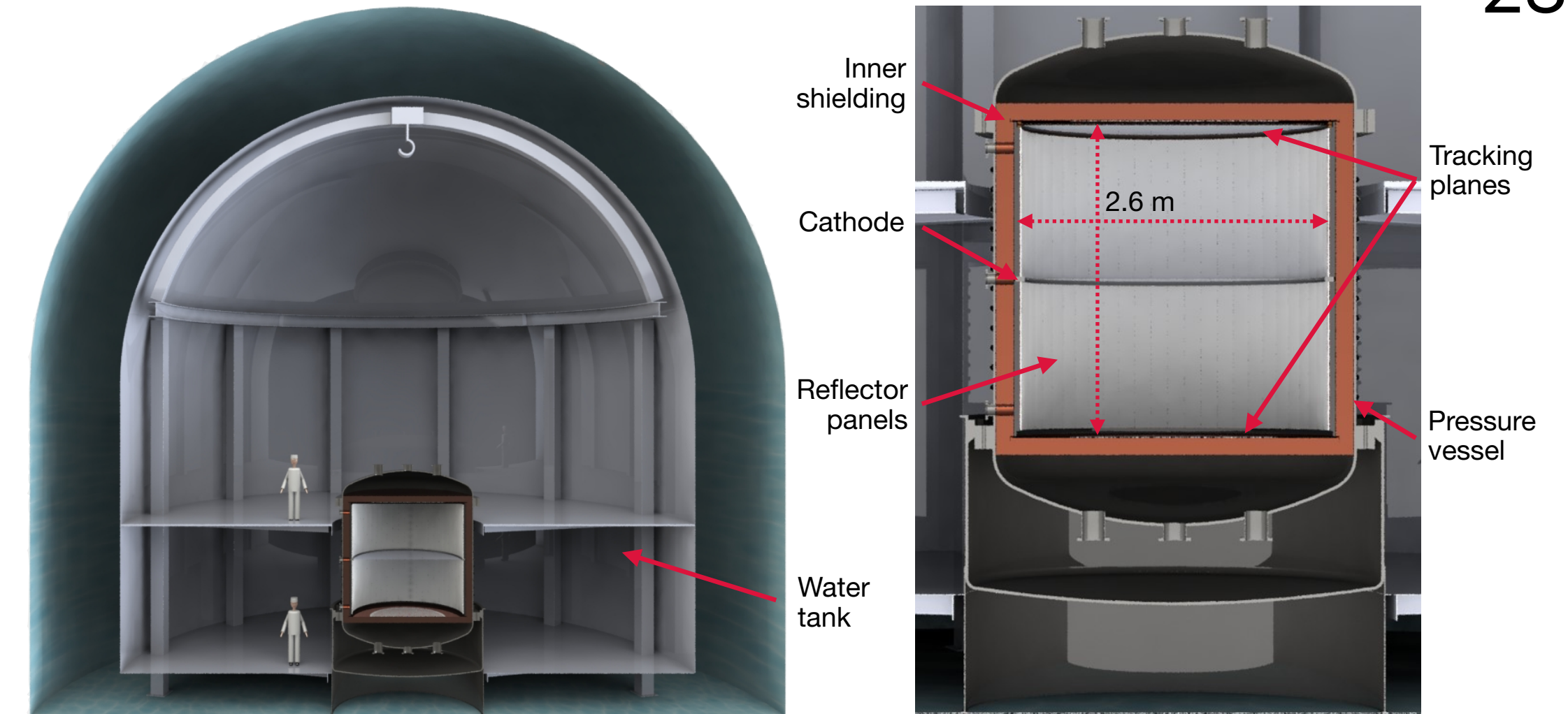
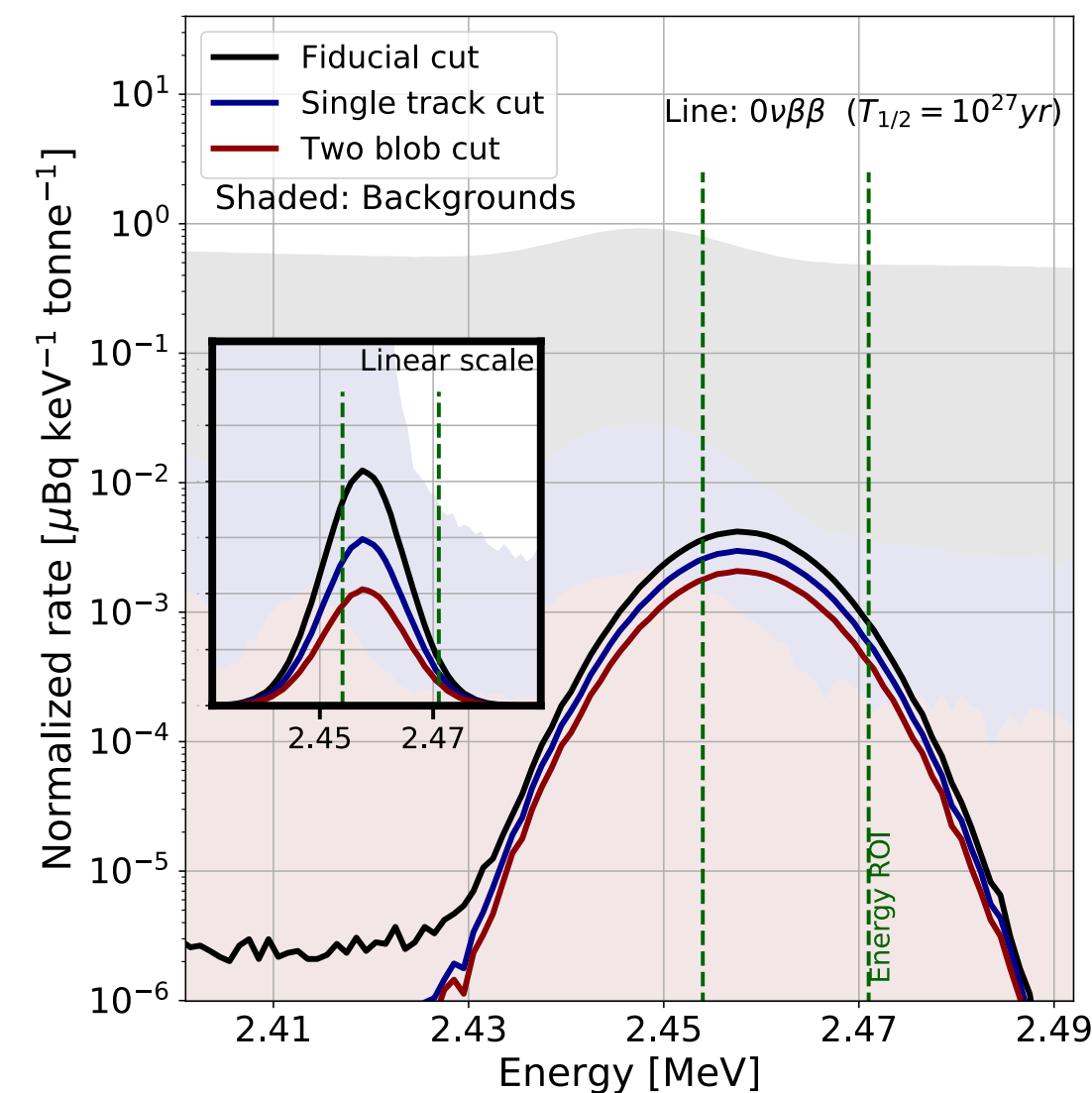
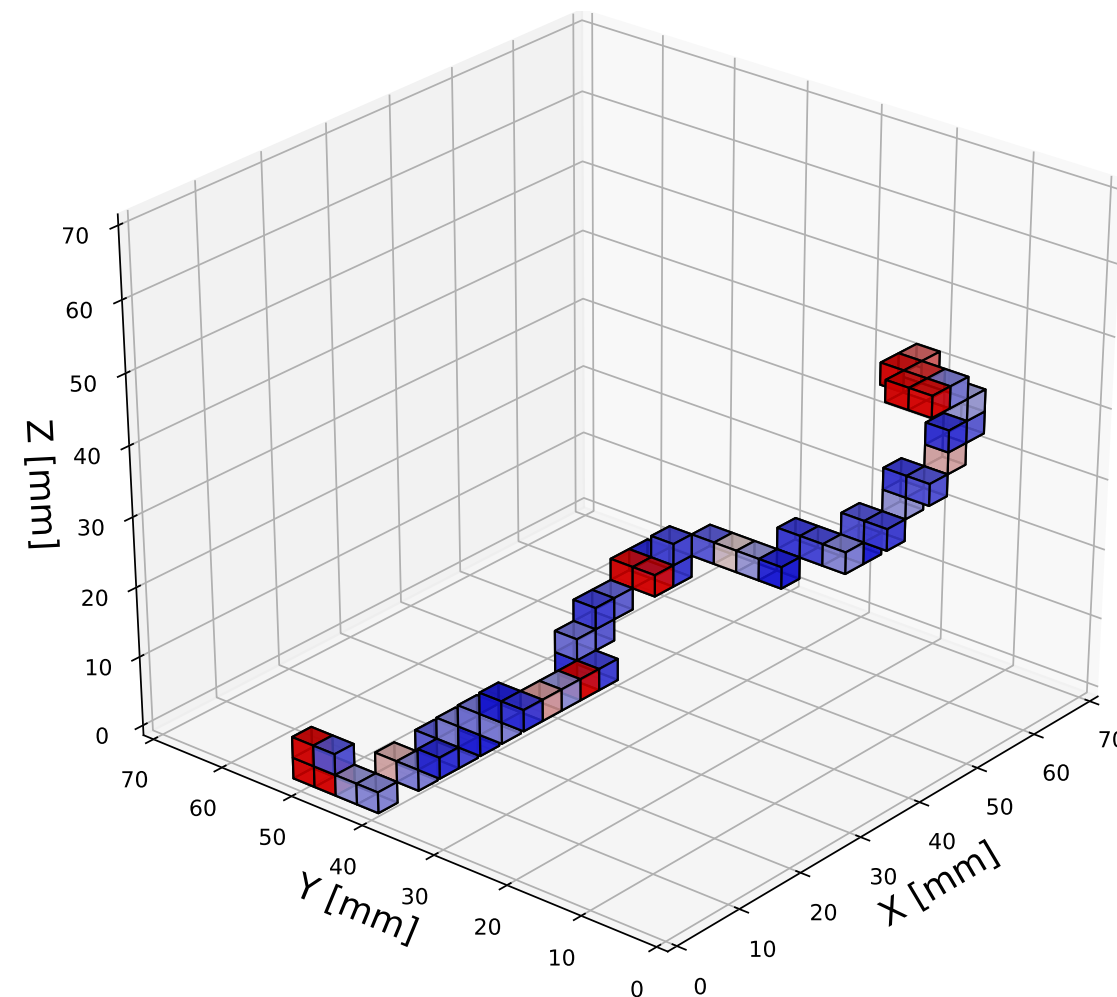
NEXT-100





NEXT-HD

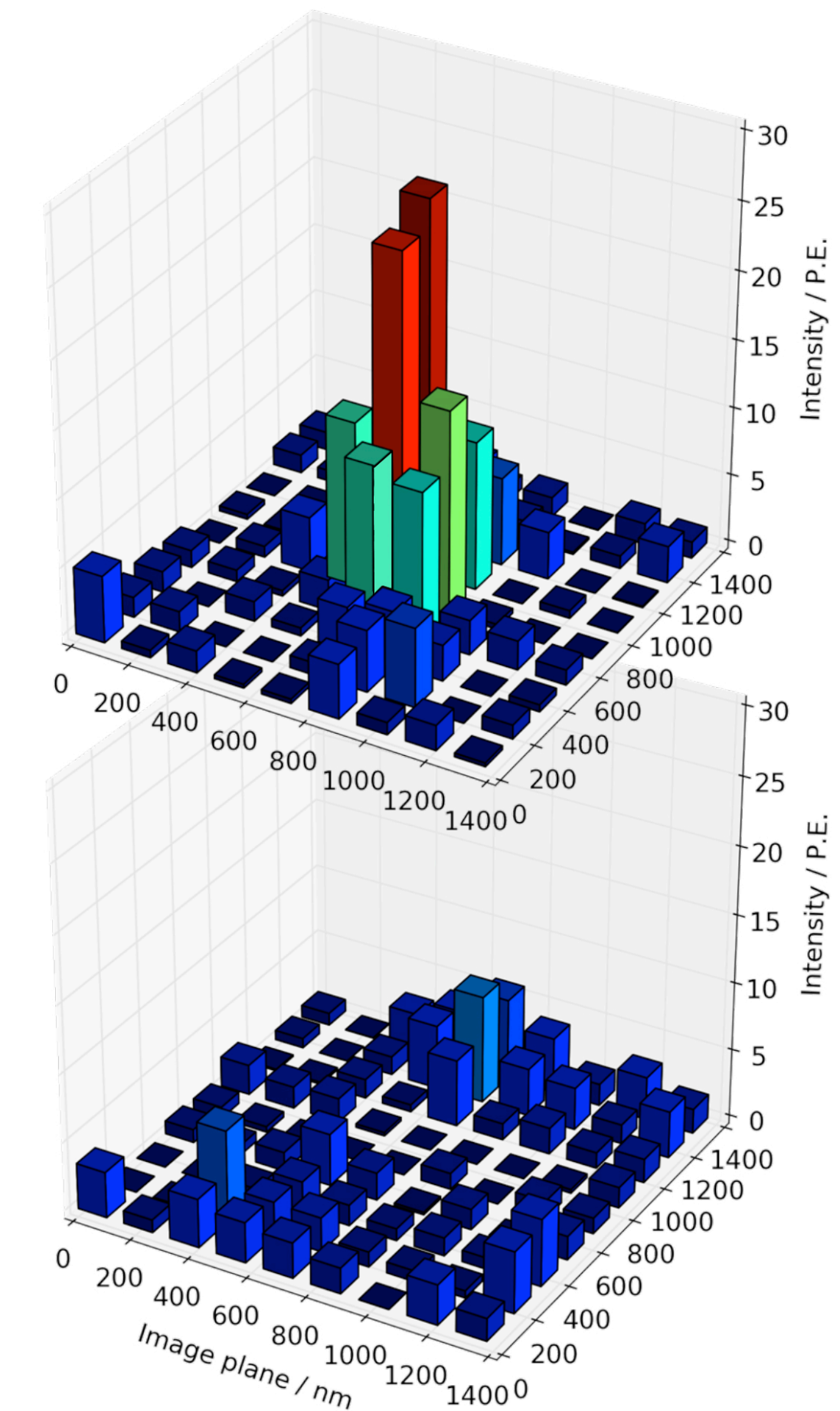
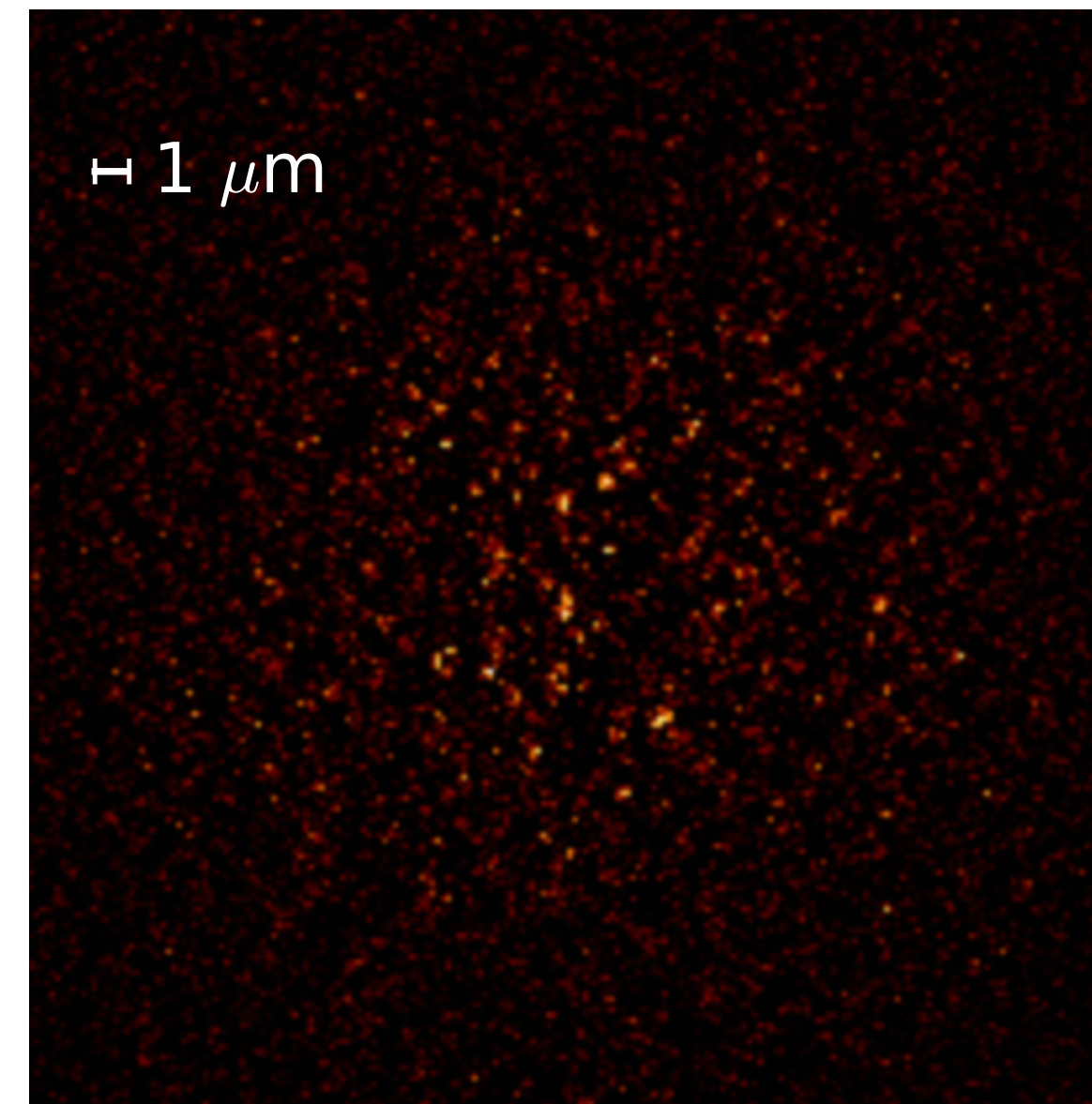
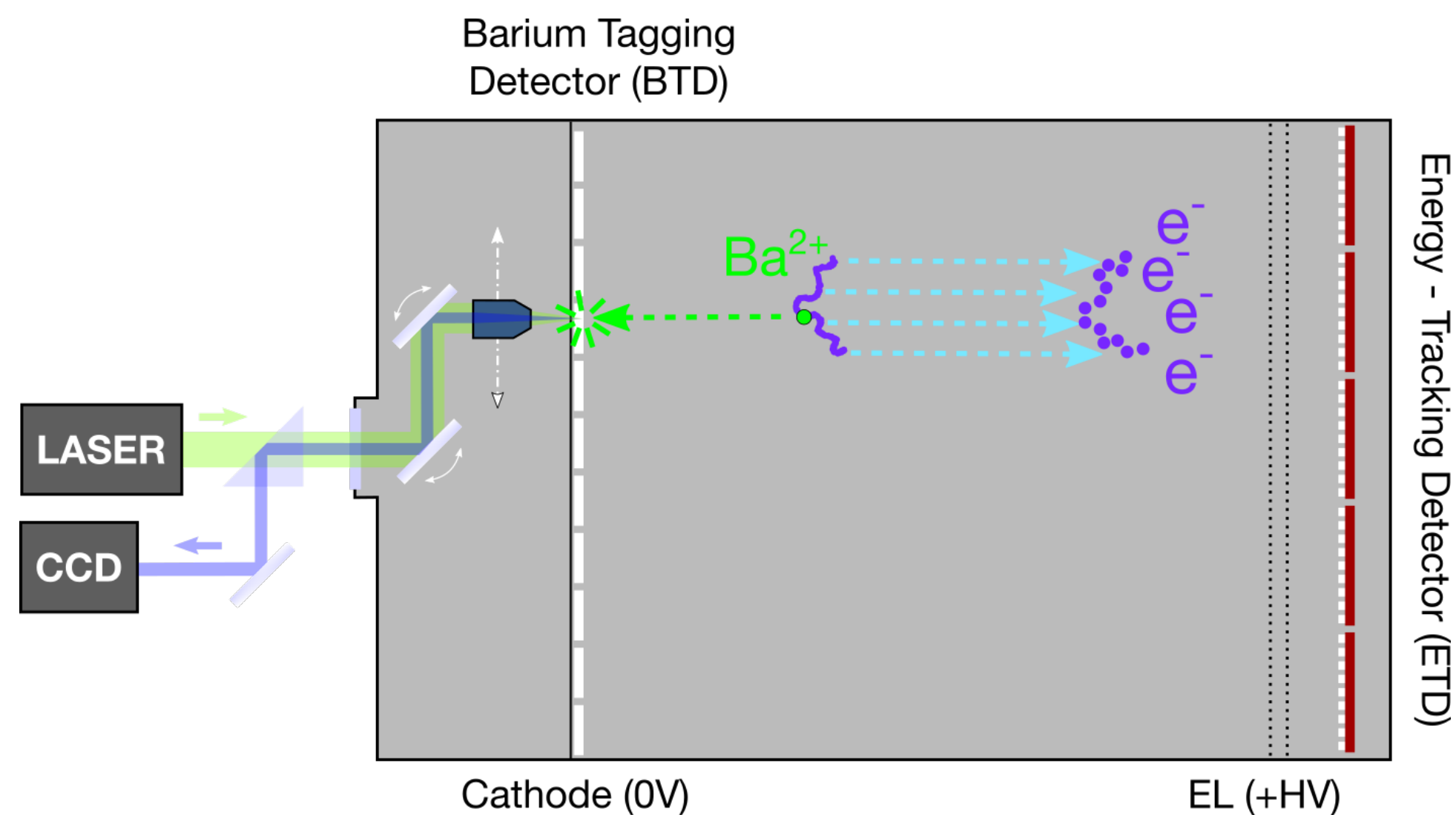
- **Experimento multi-módulo** con un primer detector de 1 tonelada de ^{136}Xe en el Laboratorio Subterráneo de Canfranc.
- Diseño base: **TPC simétrica** con cátodo central, lectura mediante un **plano denso de SiPMs** y un **barril de fibras centelladoras**.
- Fondo estimado: 0.09–0.27 cuentas / ROI / ton / yr.



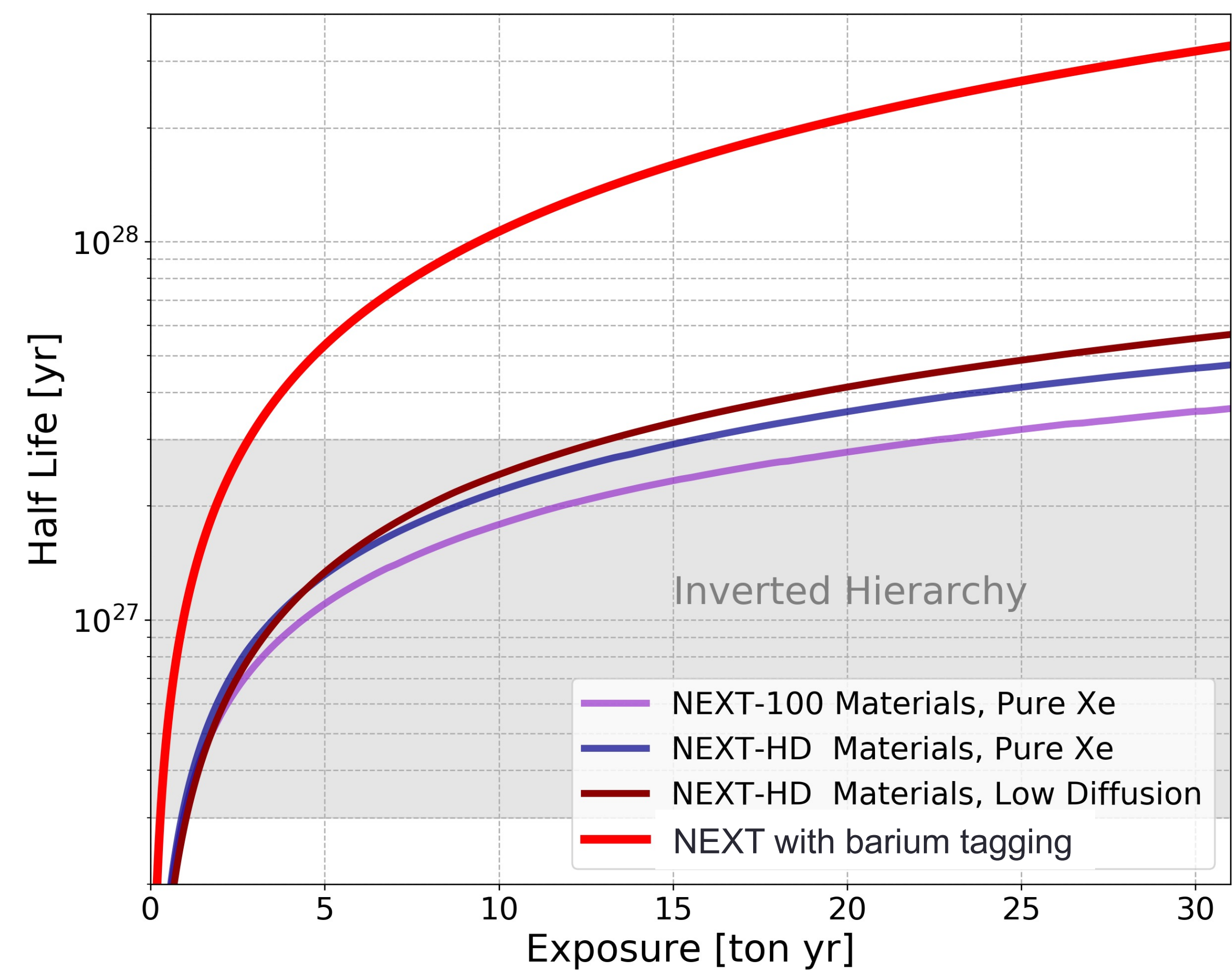
NEXT-BOLD

24

- El desarrollo de un sistema eficiente y escalable de **identificación de iones de bario** en xenón gaseoso a alta presión posibilitaría un **experimento libre de fondos**.
- NEXT utiliza *single-molecule fluorescence imaging* (SMFI) para detectar el ion Ba^{2+} producido en las desintegraciones doble beta.



SENSIBILIDAD DE NEXT EN LA ESCALA DE LA TONELADA



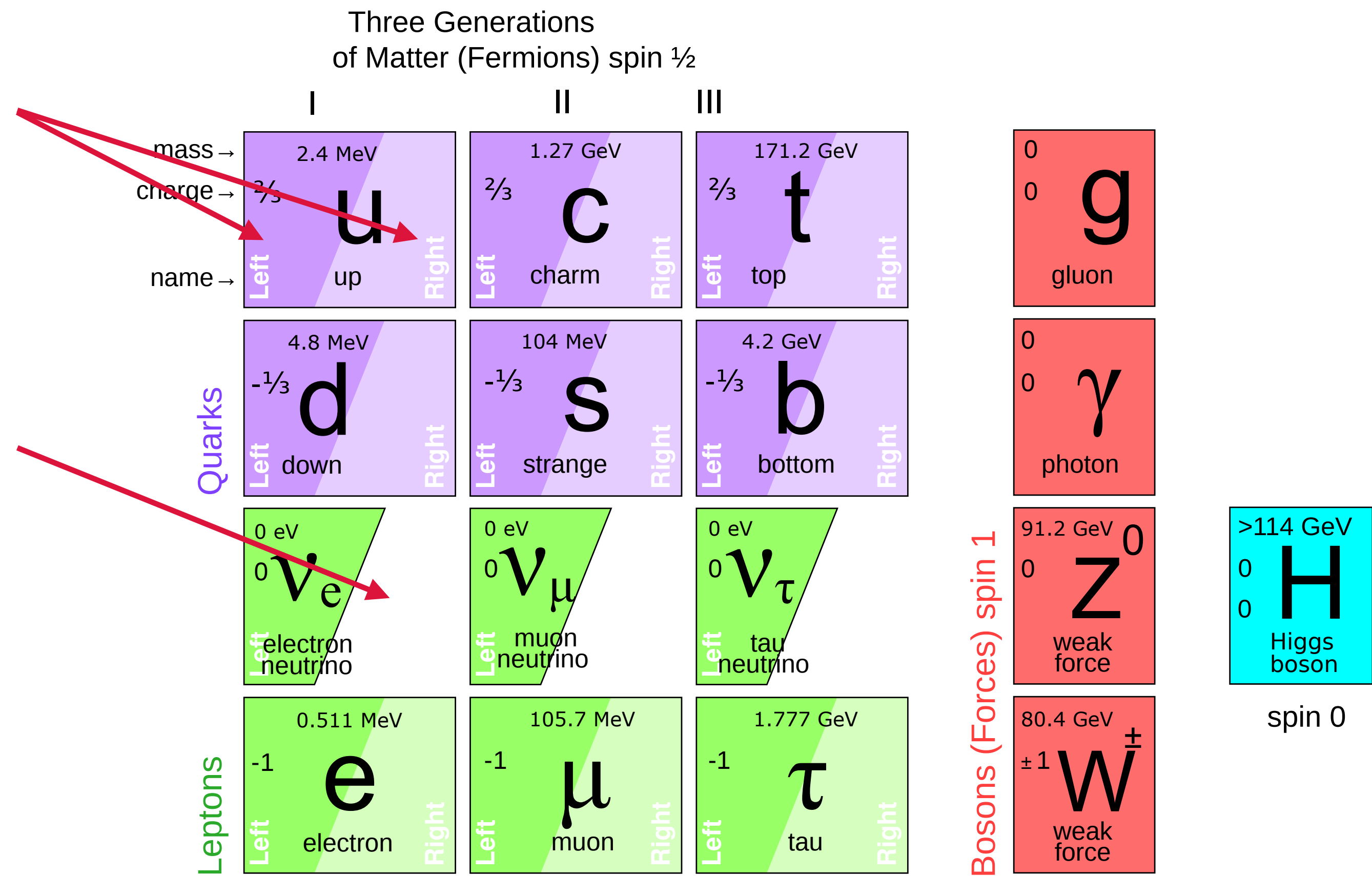
Material de apoyo

Neutrinos in the Standard Model

Fermion masses arise from the couplings of their left-handed and right-handed fields to the Higgs field.

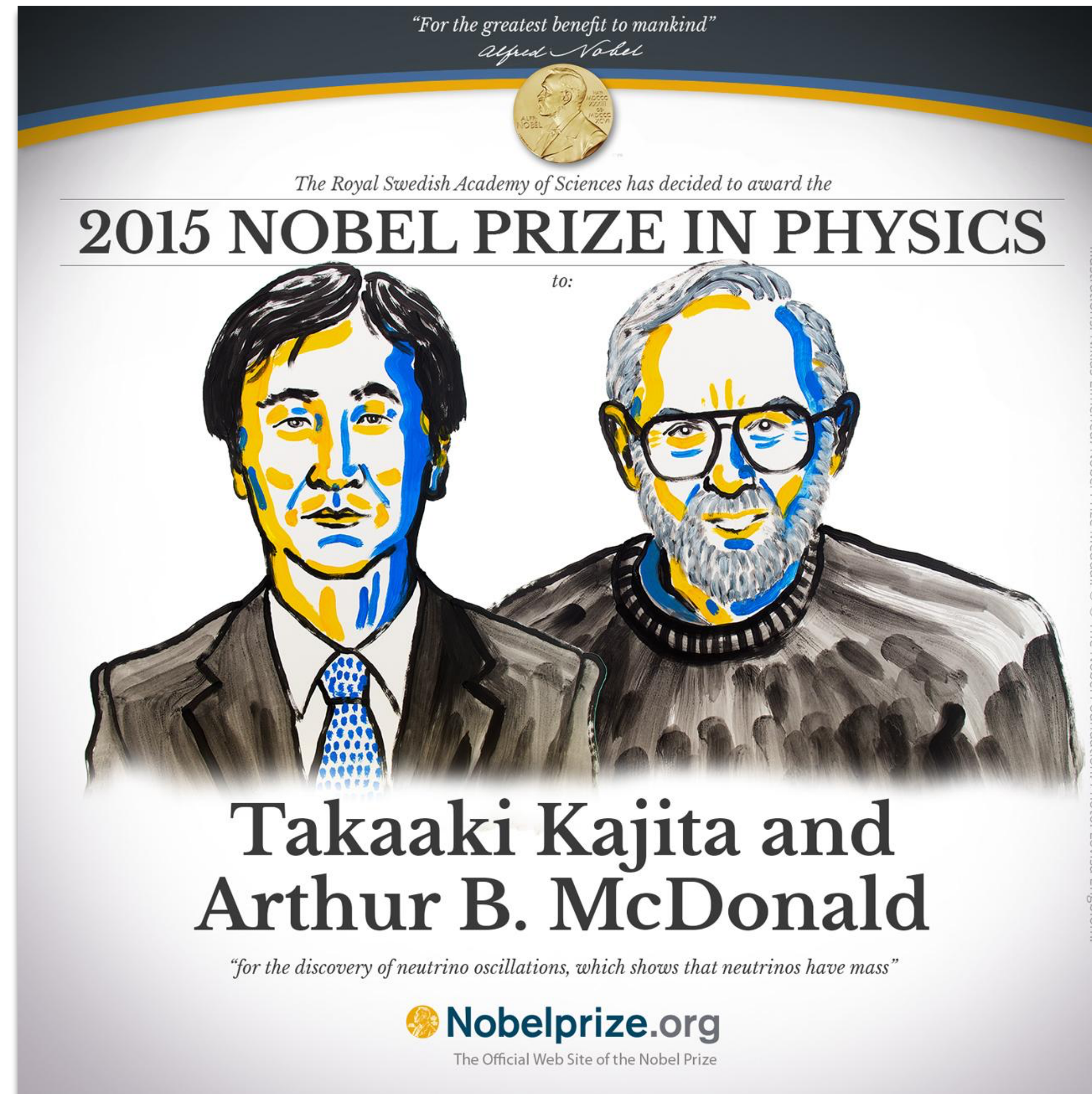
The Standard Model does not contain right-handed neutrino fields, as they'd be sterile (i.e. with no SM gauge interactions).

Therefore, neutrinos are left **massless** in the Standard Model.



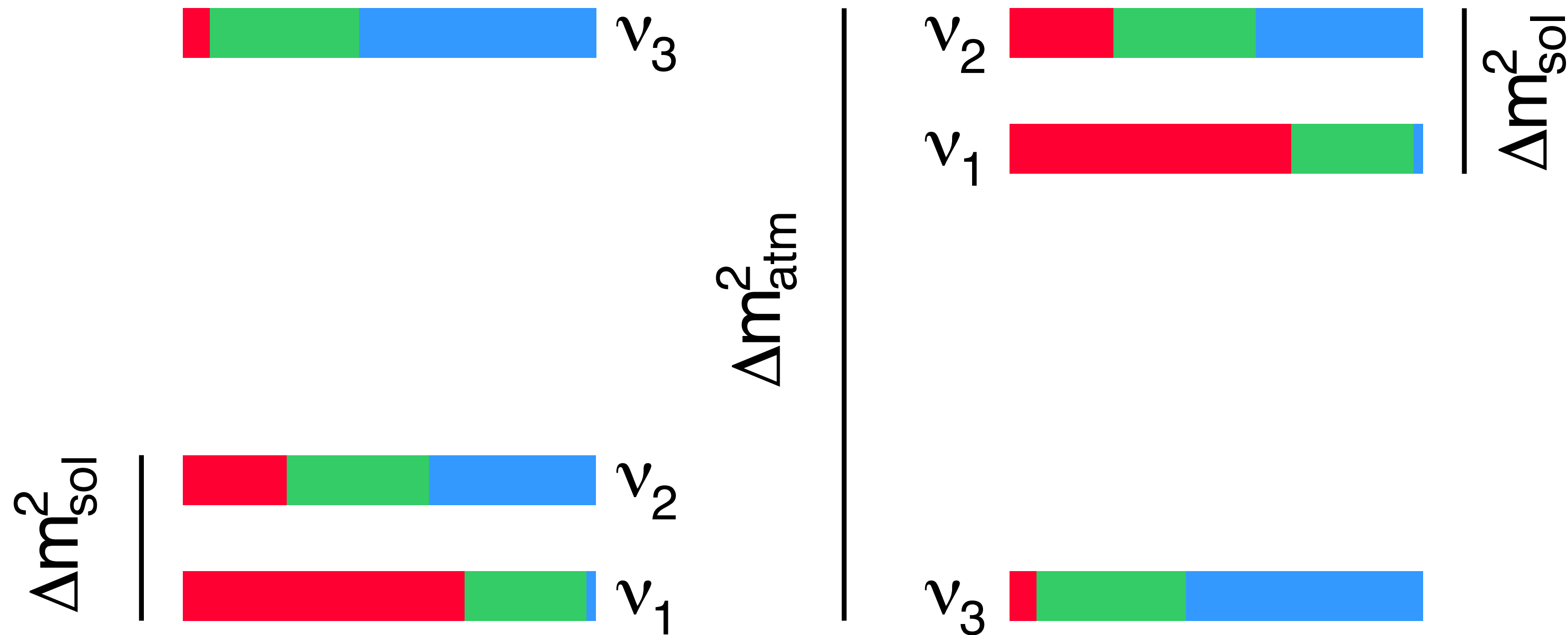
...but neutrinos have mass

28



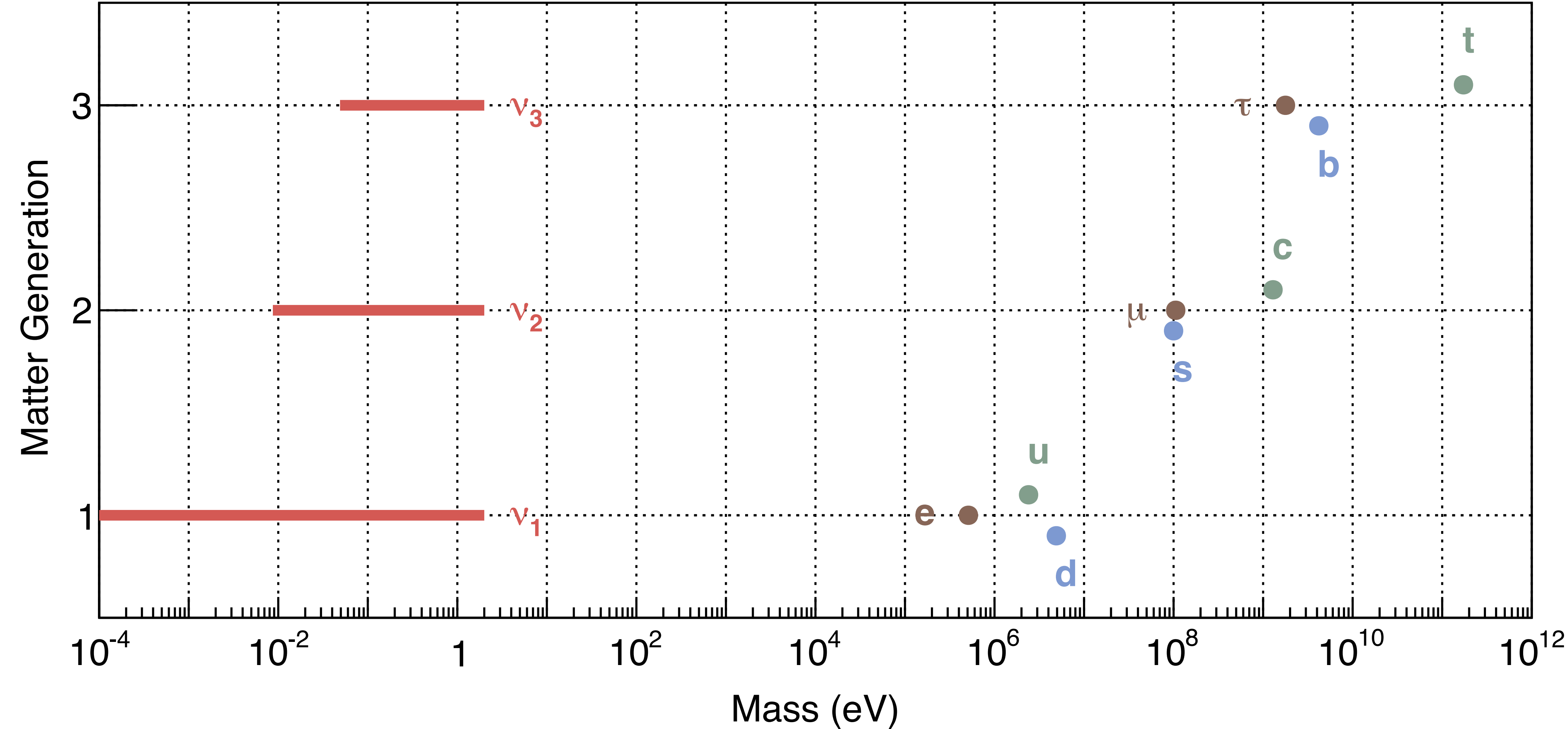
Neutrino masses and mixing

29



Oscillation experiments have established that neutrinos are massive particles and that the neutrino states participating in the weak interaction (flavour *eigenstates*) are different from the states controlling free-particle evolution (mass *eigenstates*).

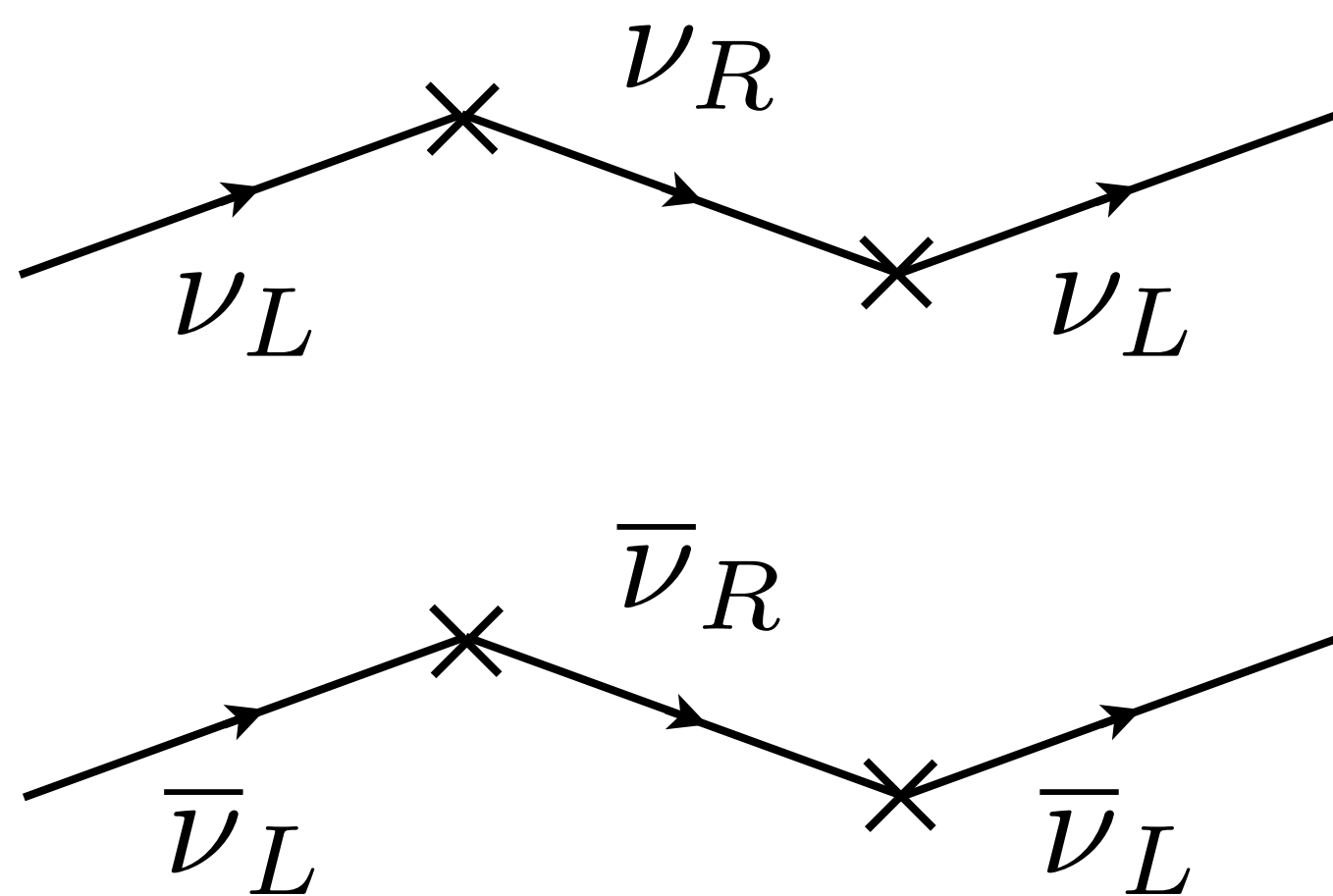
Fermion mass spectrum



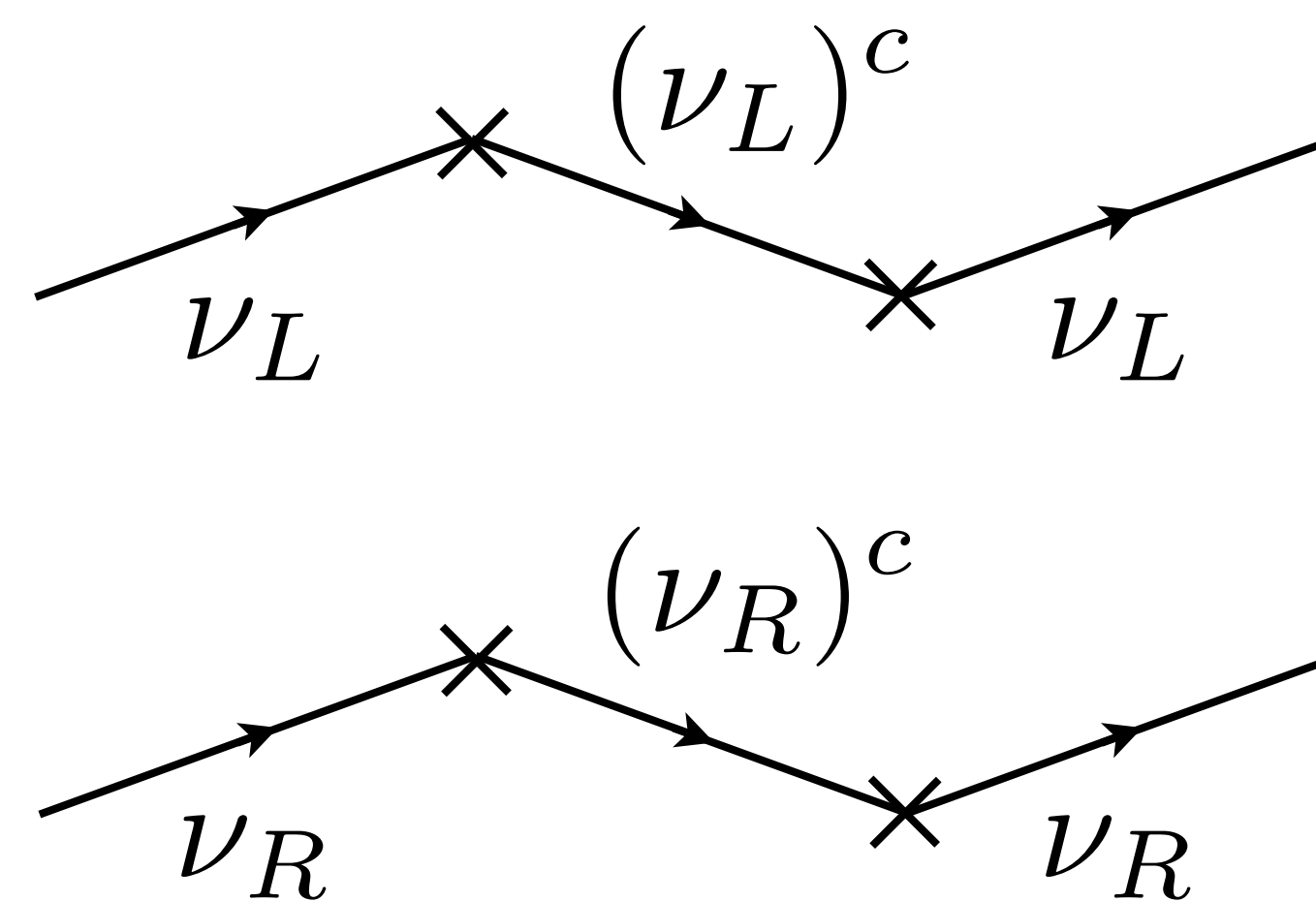
Recipes for a neutrino mass

31

Dirac mass term



Majorana mass term



Recipes for a neutrino mass

32

Dirac mass term

$$-\mathcal{L}_D = m_\nu \overline{\nu_L} \nu_R + \text{H.c}$$

- Mass term analogous to those of charged leptons.
- Sterile right-handed fields added to the Standard Model.
- Conserves lepton number.

Majorana mass term

$$-\mathcal{L}_M = m_\nu \overline{\nu_L} \nu_L^c + \text{H.c}$$

- Requires an expanded Higgs sector.
- Implies lepton number violation.
- Neutrinos and antineutrinos are identical.

Recipes for a neutrino mass

33

Dirac mass term

$$m_\nu \sim y_\nu v$$

- Mass proportional to Higgs VEV.
- Unexplained very small couplings needed to account for observed neutrino masses.

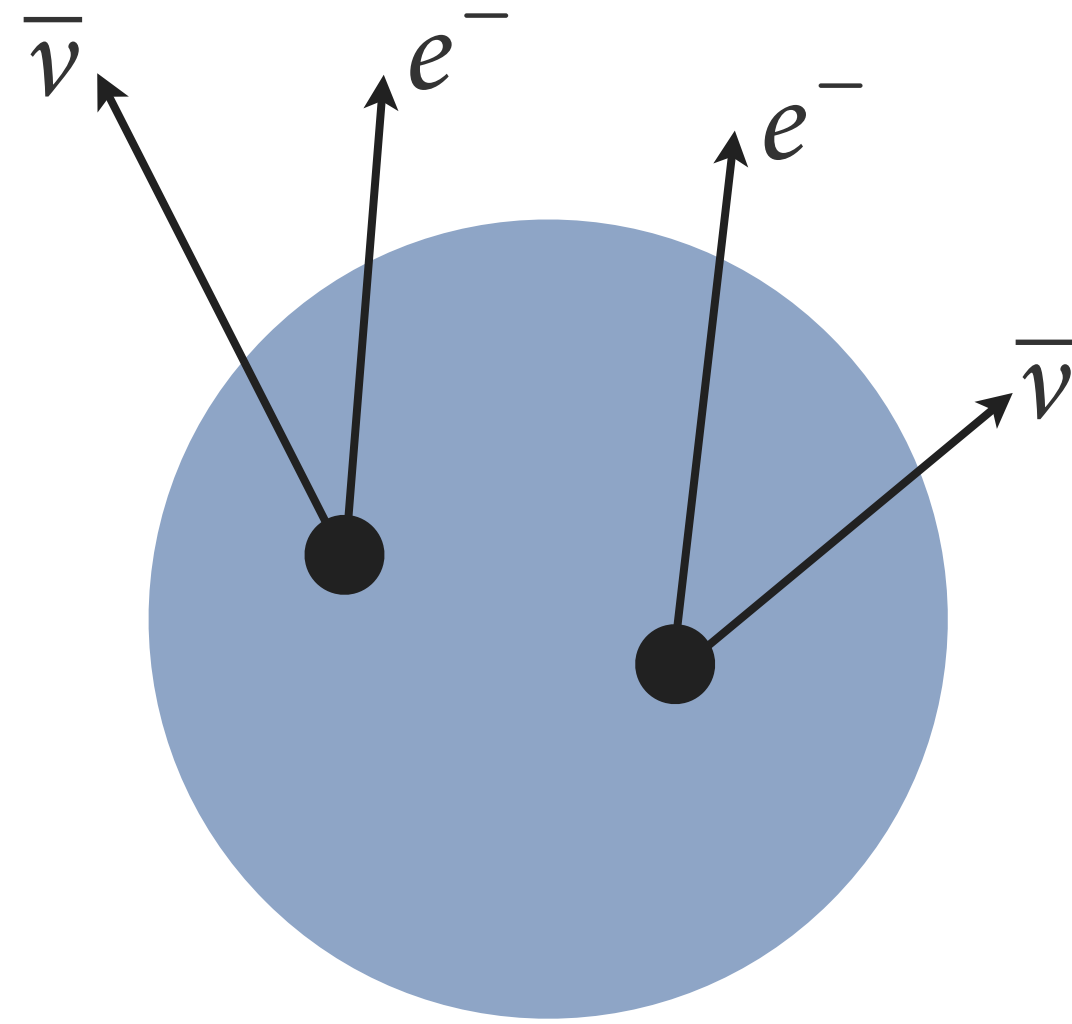
Majorana mass term

$$m_\nu \sim y_\nu v^2 / M$$

- Hint of a new physics scale responsible for the strong hierarchy between neutrino and charged-lepton masses.

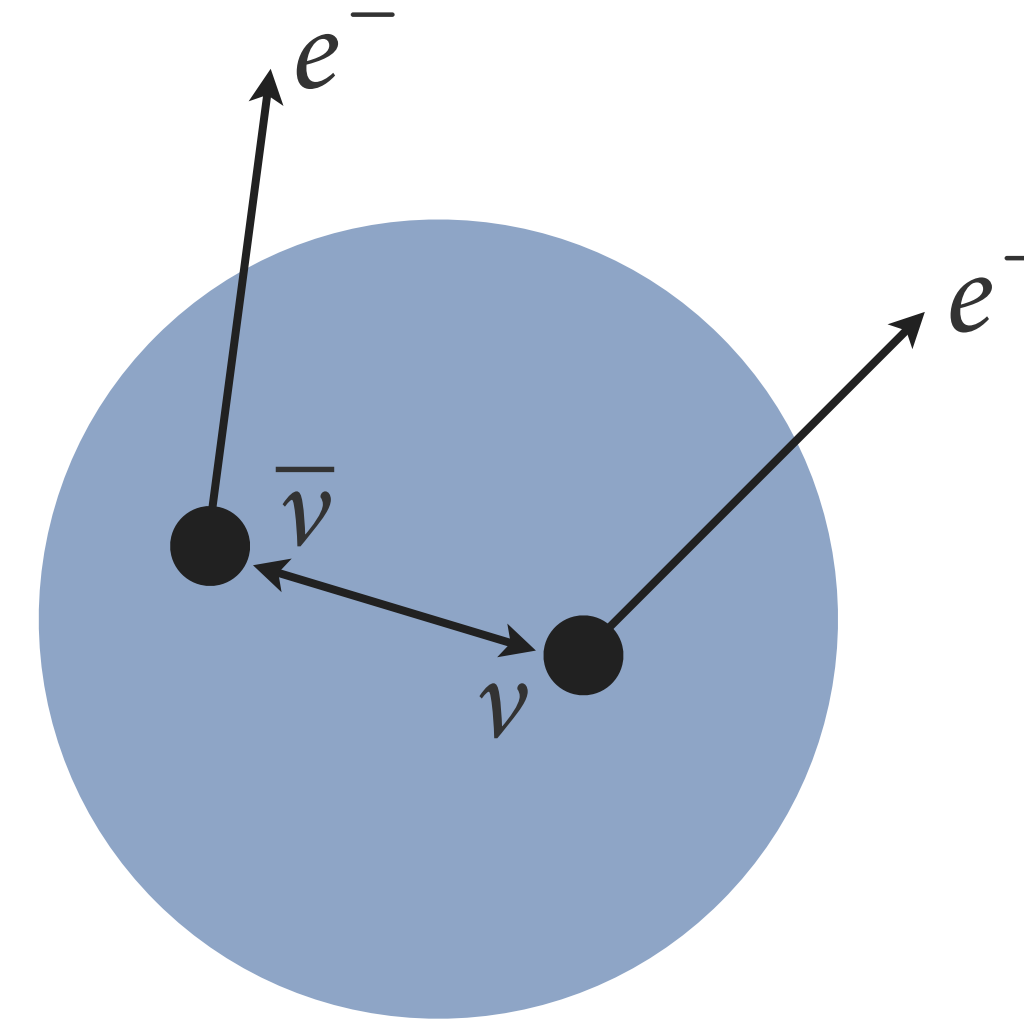
Double beta decay

34



$2\nu\beta\beta$

SM-allowed process. Observed in several isotopes with half-lives of order $10^{18} - 10^{22}$ years.

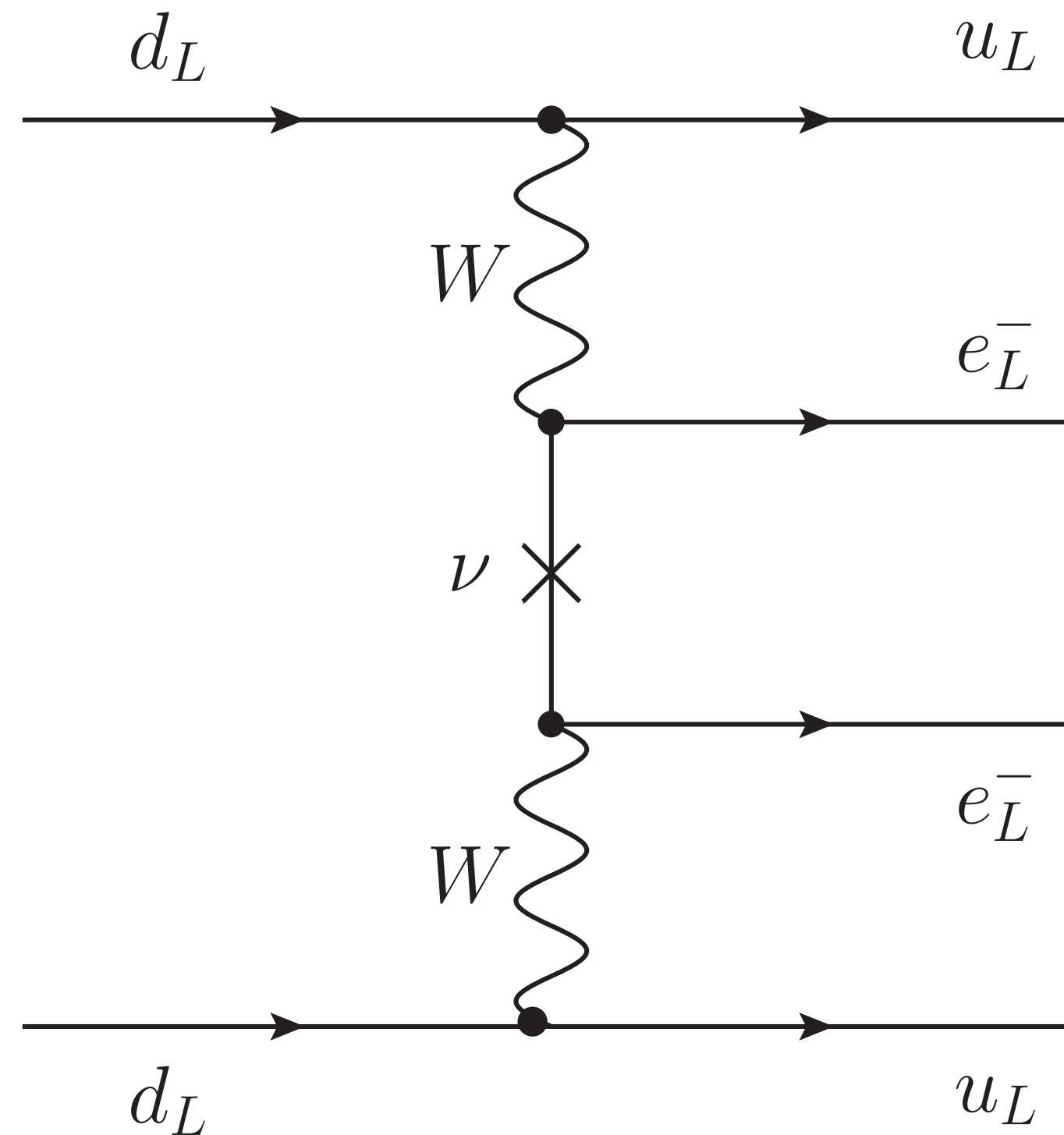


$0\nu\beta\beta$

Forbidden in SM. Violates total lepton number ($\Delta L=2$). Half-life longer than 10^{26} years.

Majorana neutrinos and $0\nu\beta\beta$

35



The simplest underlying mechanism for neutrinoless double beta decay is the virtual exchange of a light Majorana neutrino. However, irrespectively of the mechanism, the existence of neutrinoless double beta decay implies a Majorana mass term for neutrinos [Schechter and Valle, *PRD* **25** (1982) 2951].

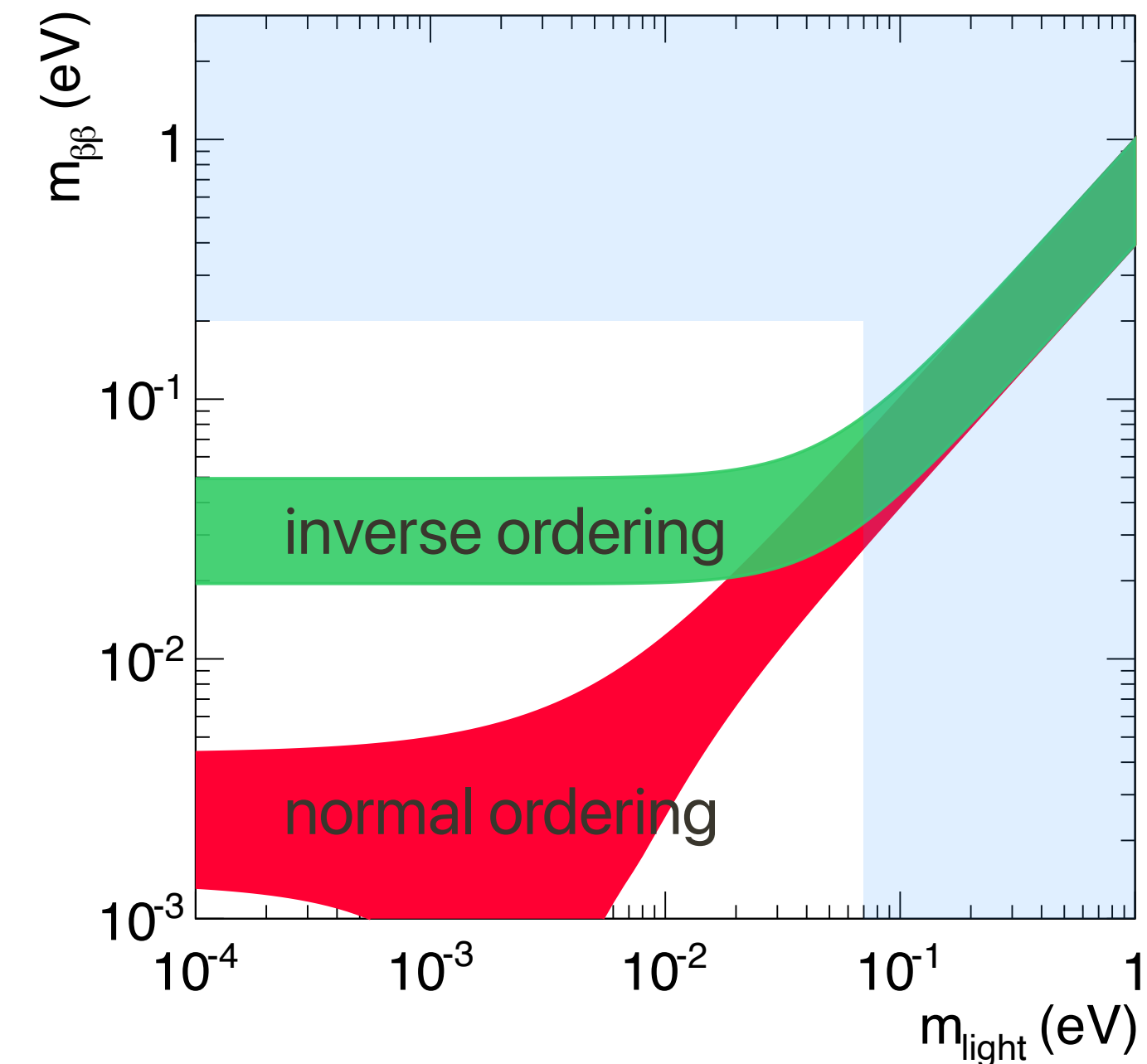
Decay rate

36

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Nuclear matrix element
(nuclear physics)
Effective Majorana mass
(particle physics)

Phase-space integral
(atomic physics)



$$m_{\beta\beta} = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|$$

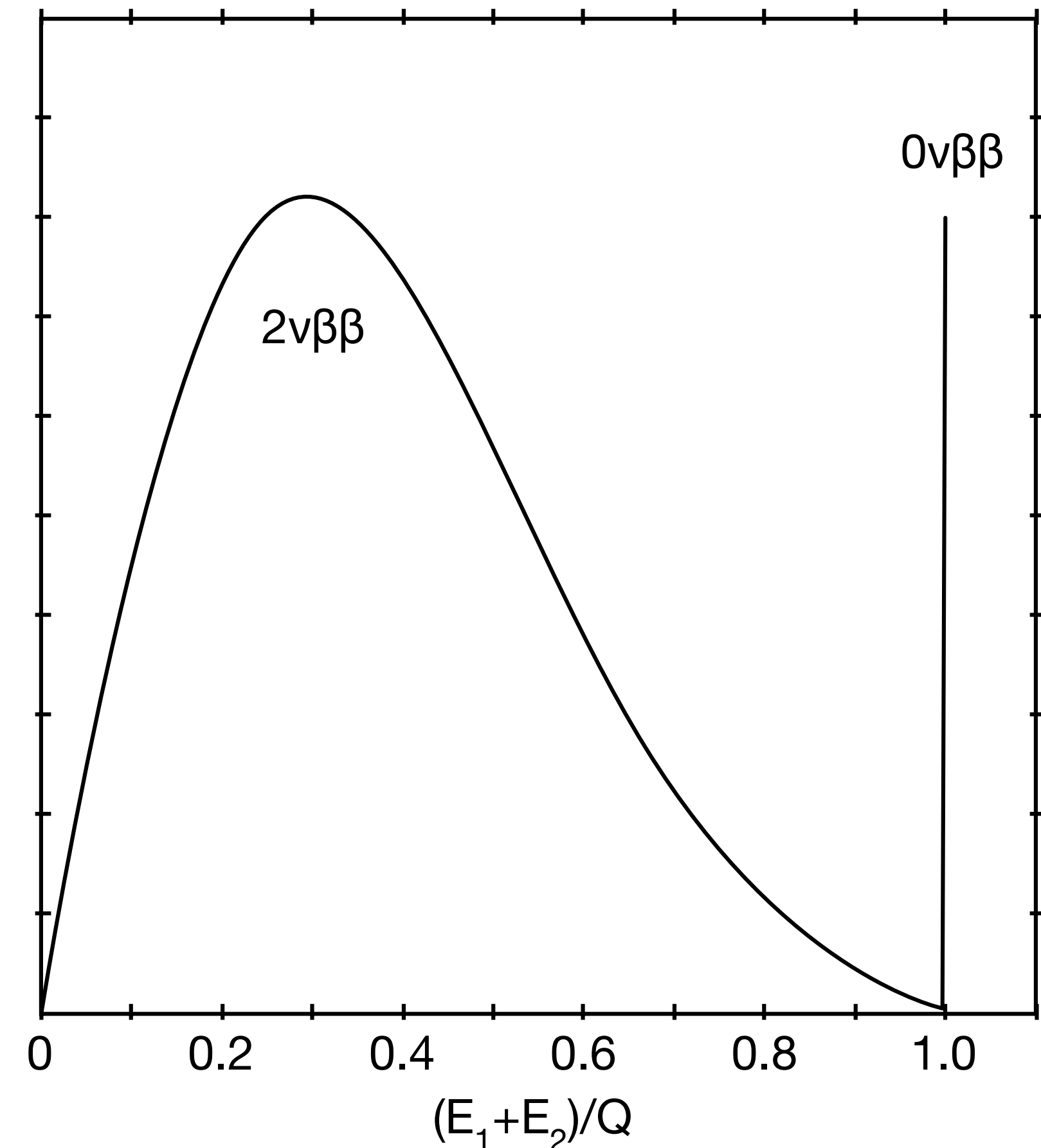
(If light neutrino exchange is the dominant underlying mechanism.)

Build your own $0\nu\beta\beta$ experiment

37

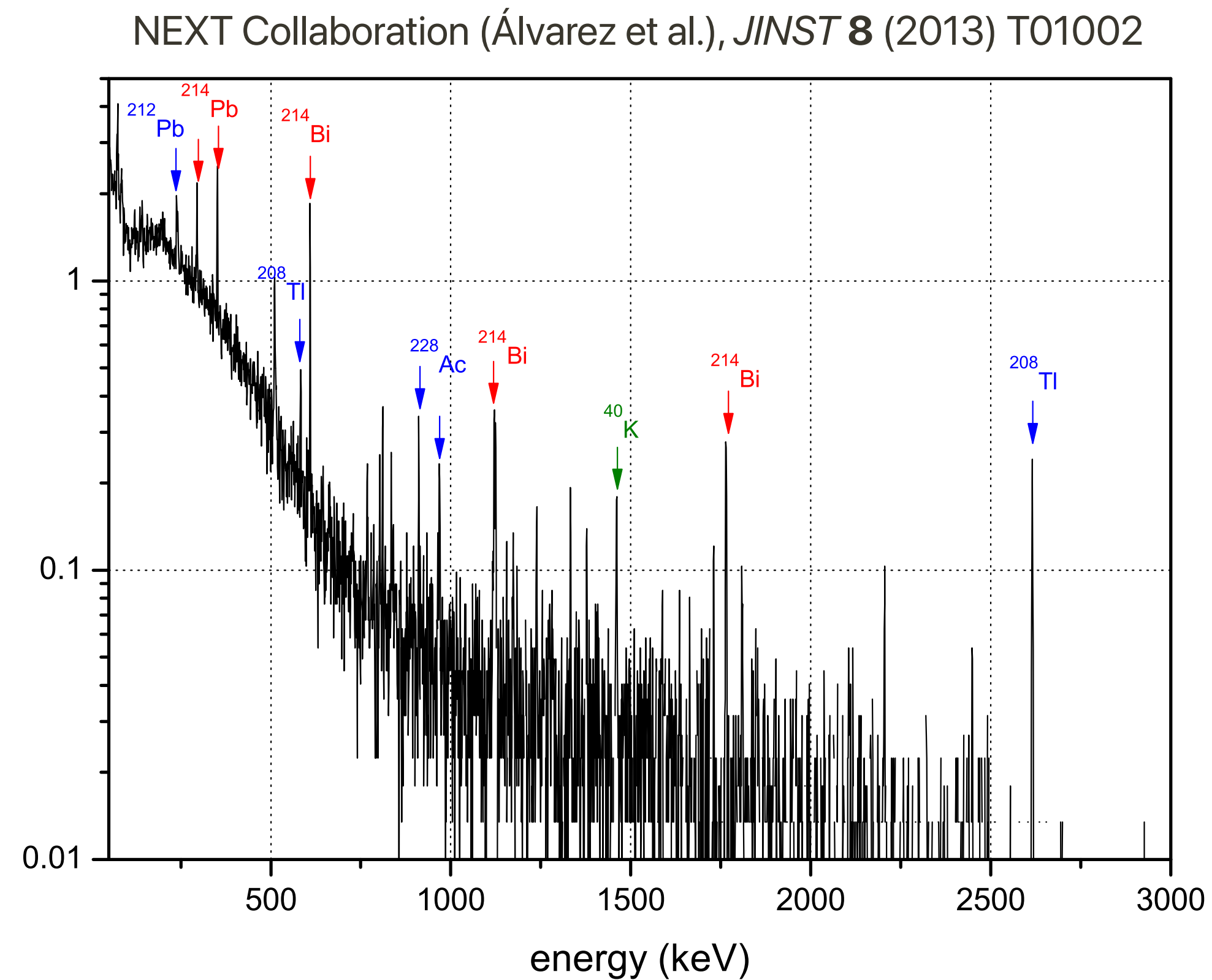
1. Acquire a large mass (M) of a double-beta-decaying isotope and a calorimeter with perfect resolution and efficiency.
2. Measure the energy of the radiation emitted by the source to separate the two different decay modes.
3. Count the number of neutrinoless decays (N) that have occurred in a given time (t) and calculate the corresponding half-life:

$$T_{1/2} = \log 2 \frac{N_A}{W} \frac{M t}{N}$$



Backgrounds

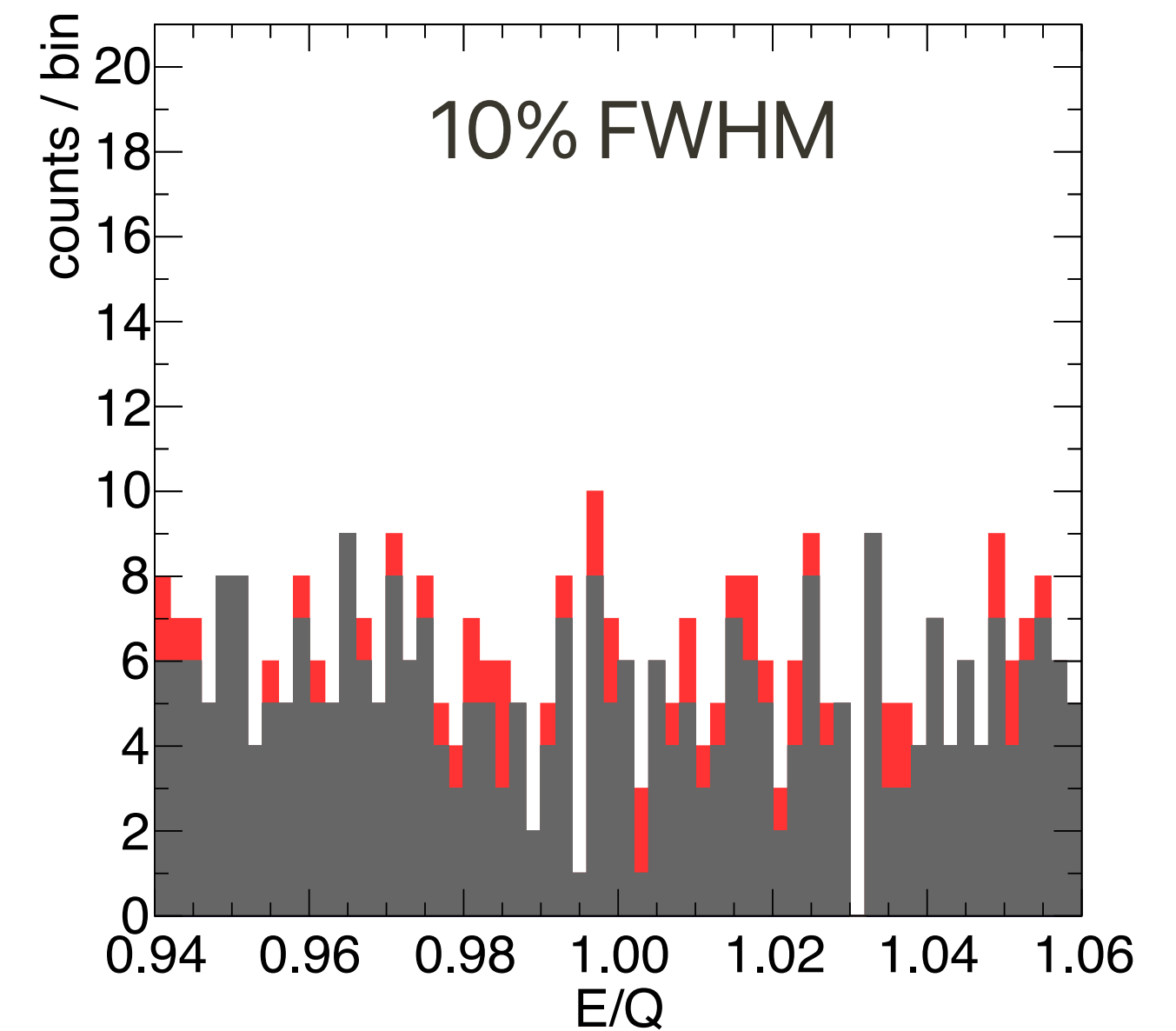
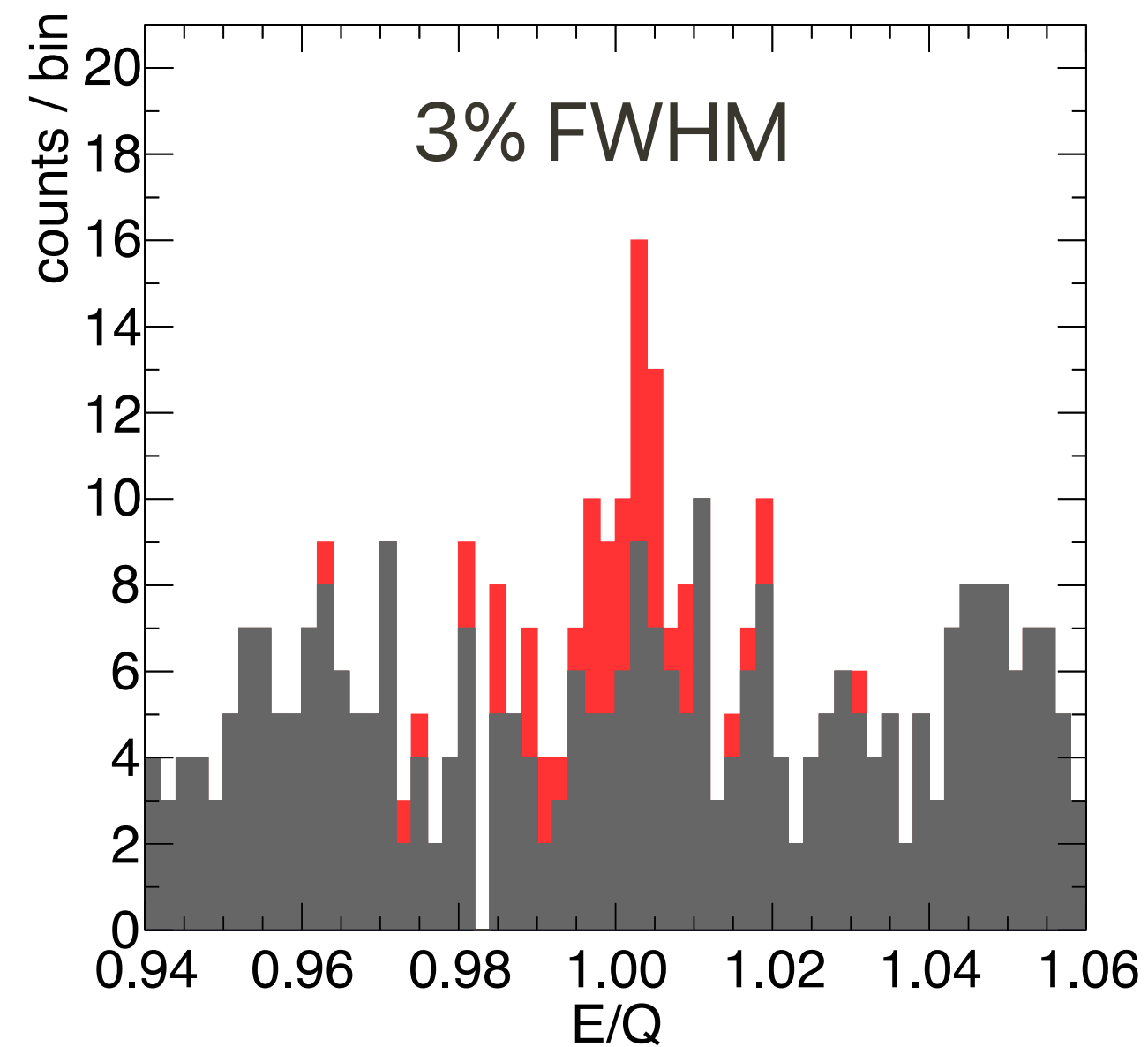
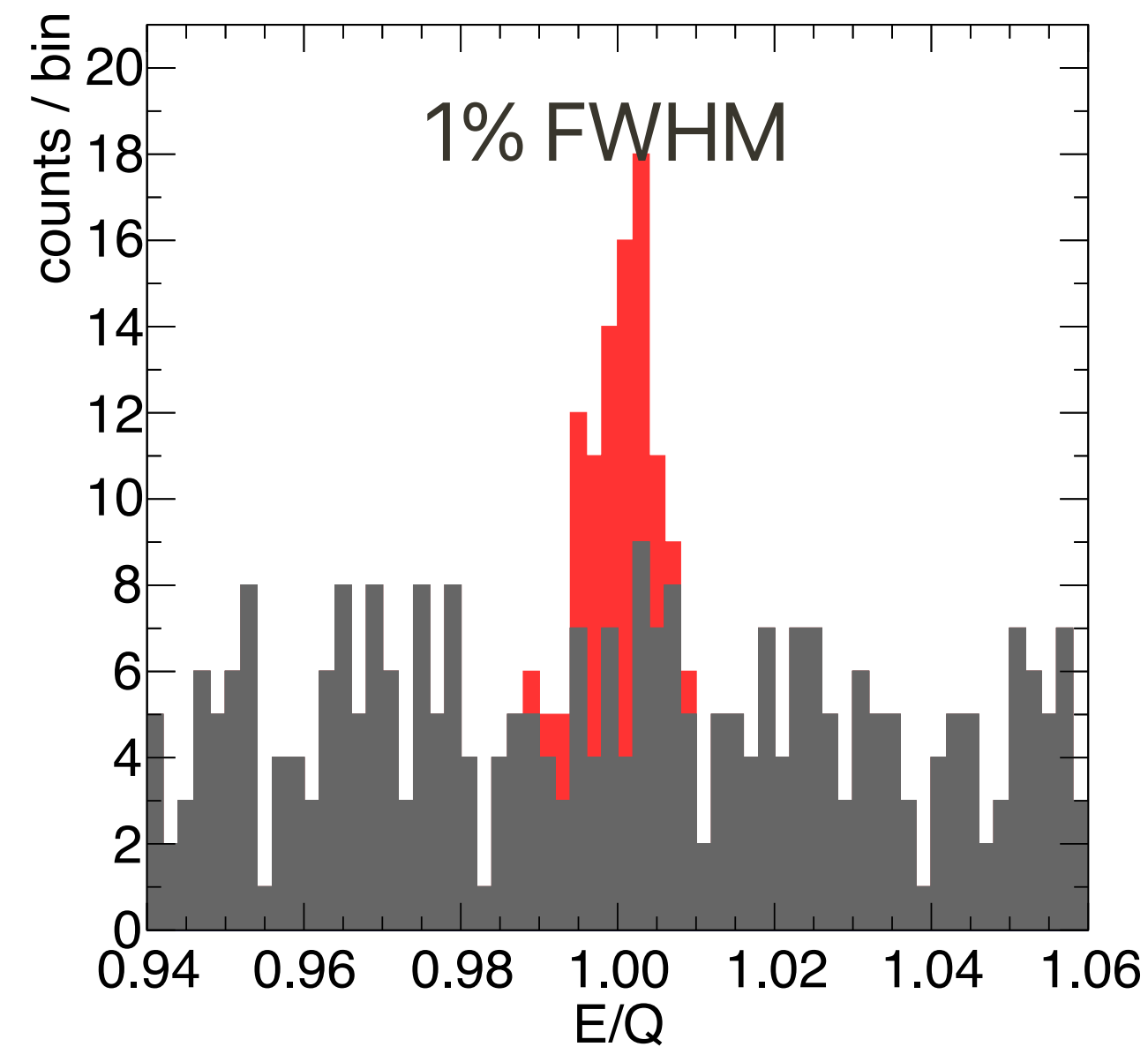
38



Natural radioactivity is the most common background for neutrinoless double beta decay experiments. The figure shows a typical energy spectrum of a high-purity germanium calorimeter.

Energy resolution

39



Good energy resolution is essential: it increases the signal to noise ratio and is the only protection against the standard two-neutrino decay mode.

Radiopurity

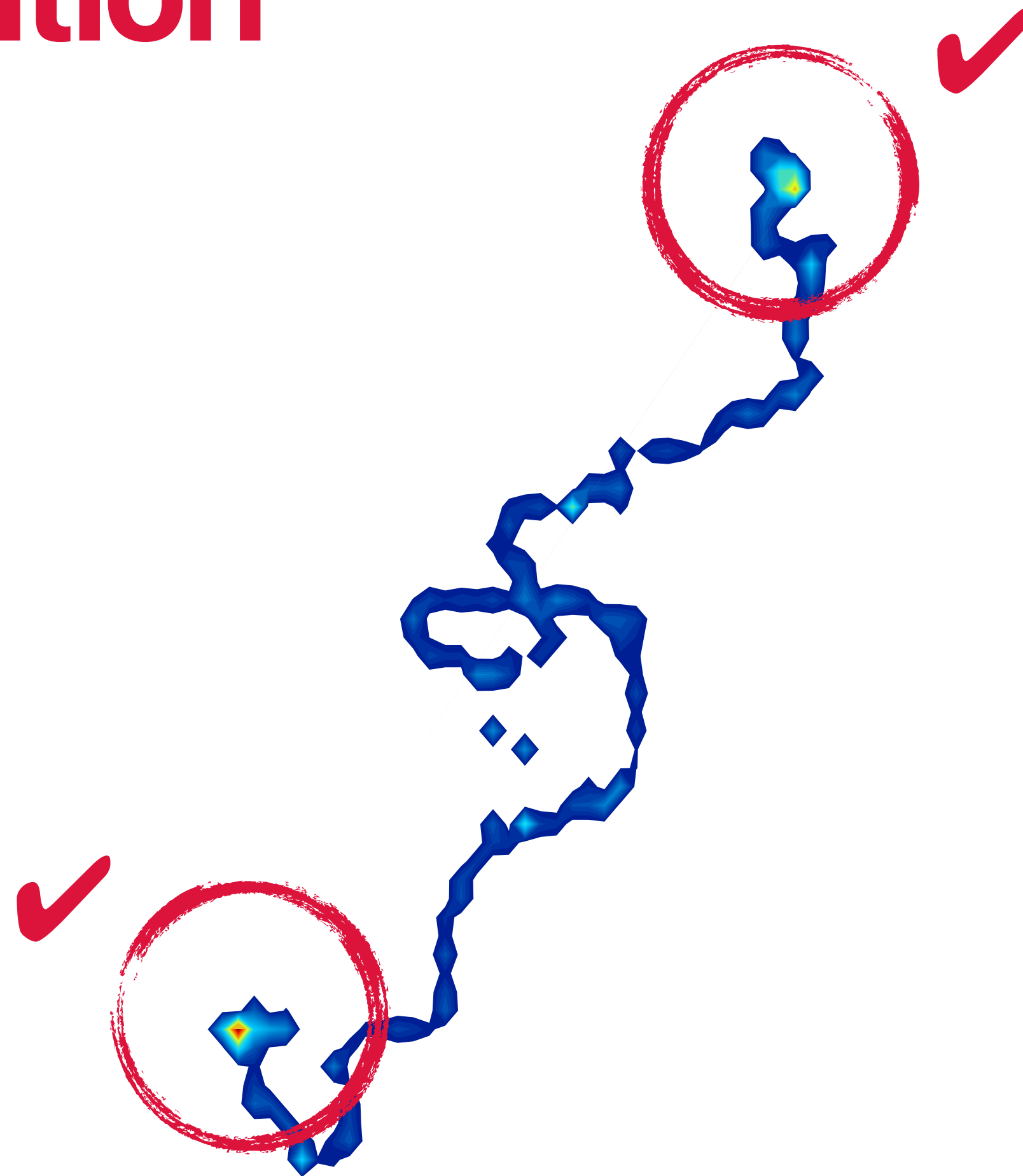
40



Detectors are being built with materials with activities as low as 10^{-6} Bq/kg.
(Compare that with typical activity of human body of about 100 Bq/kg.)

Event identification

41



All experiments look for extra signatures (e.g. event topology or pulse-shape discrimination) to differentiate signal and background events.

Experimental figure of merit

42

$$\mathcal{S}(m_{\beta\beta}) \propto \sqrt{\frac{1}{\varepsilon M t}}$$

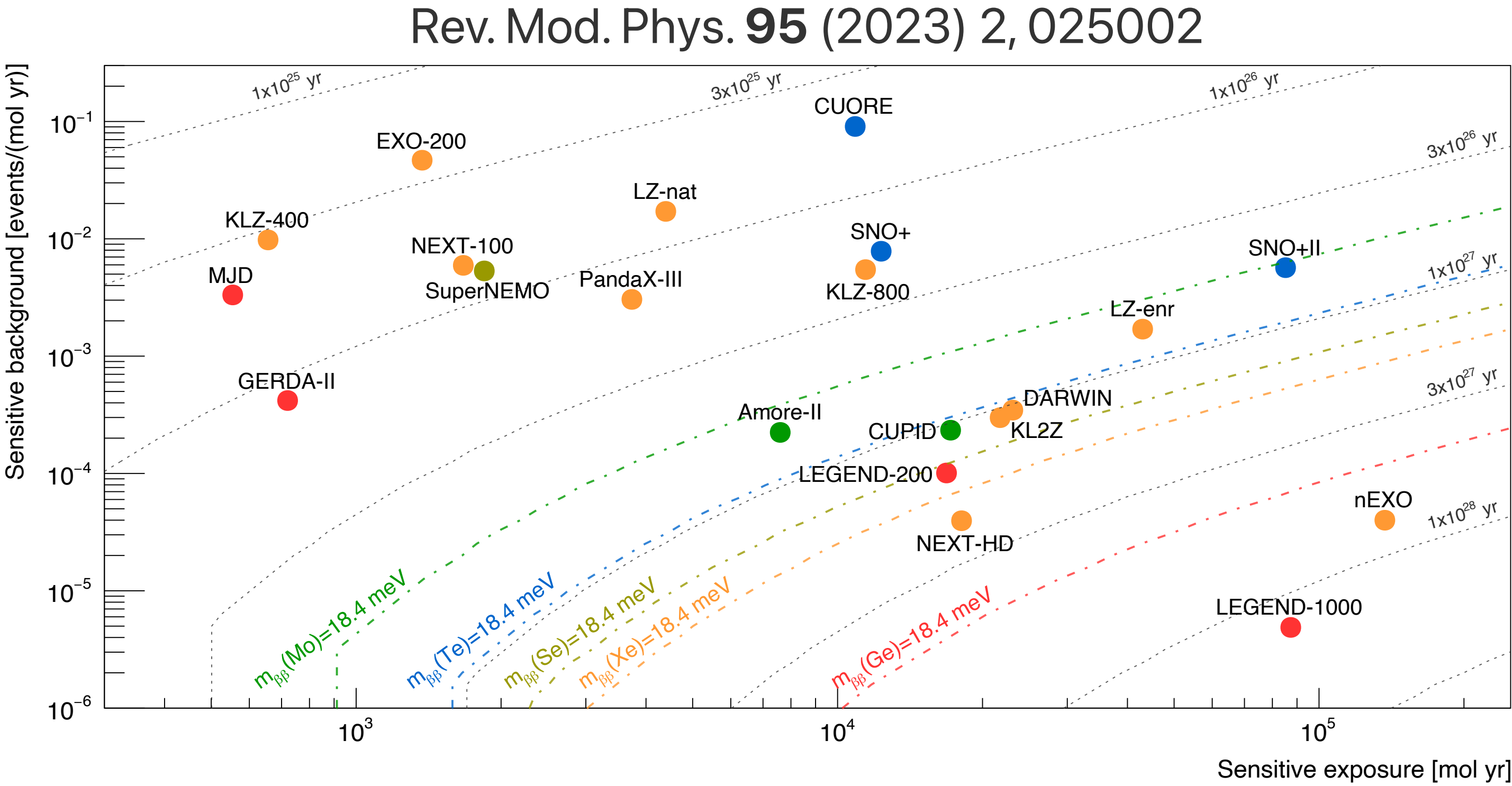
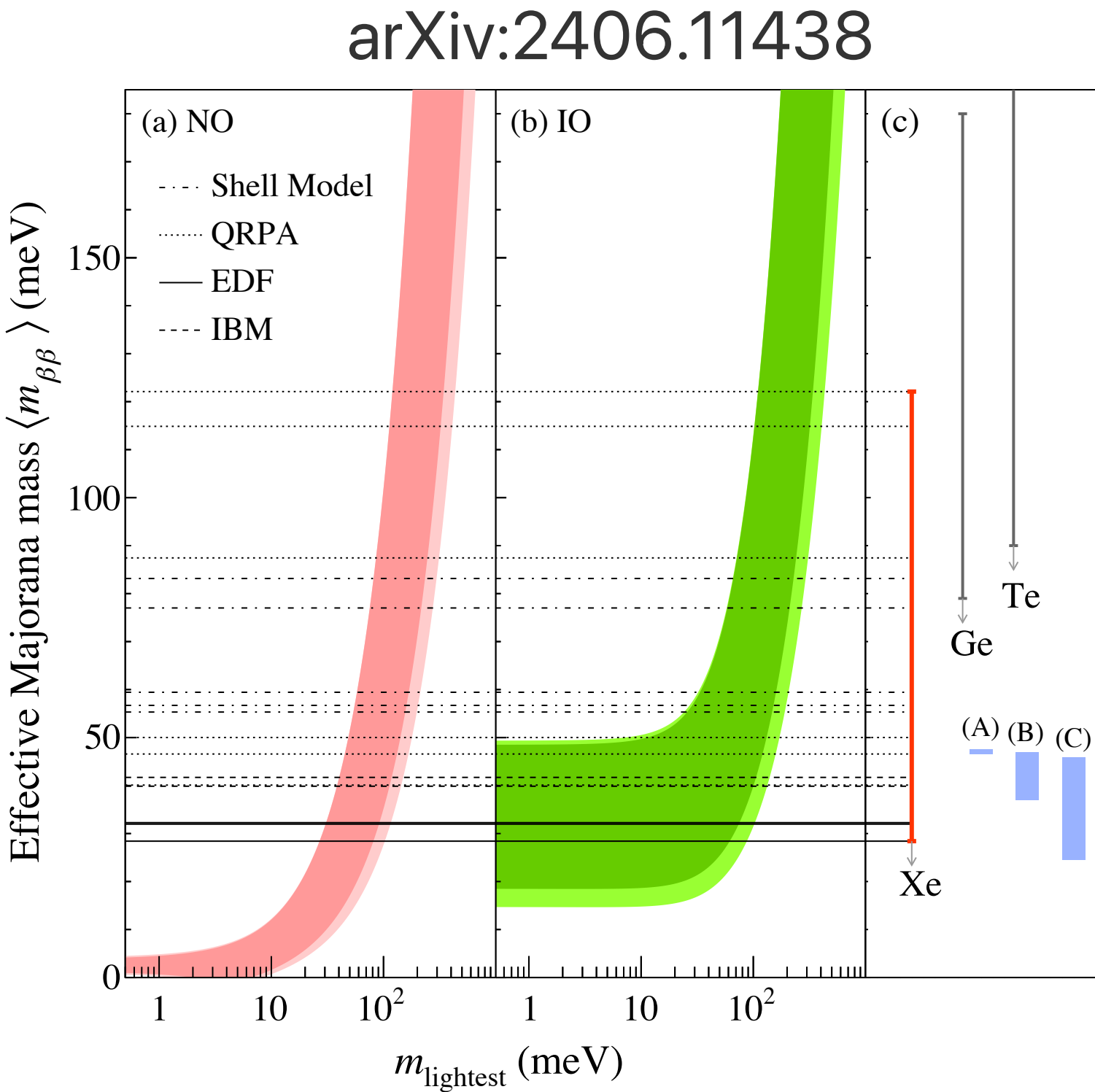
Background-free experiment

$$\mathcal{S}(m_{\beta\beta}) \propto \sqrt{1/\varepsilon} \left(\frac{b \Delta E}{M t} \right)^{1/4}$$

Background-limited experiment

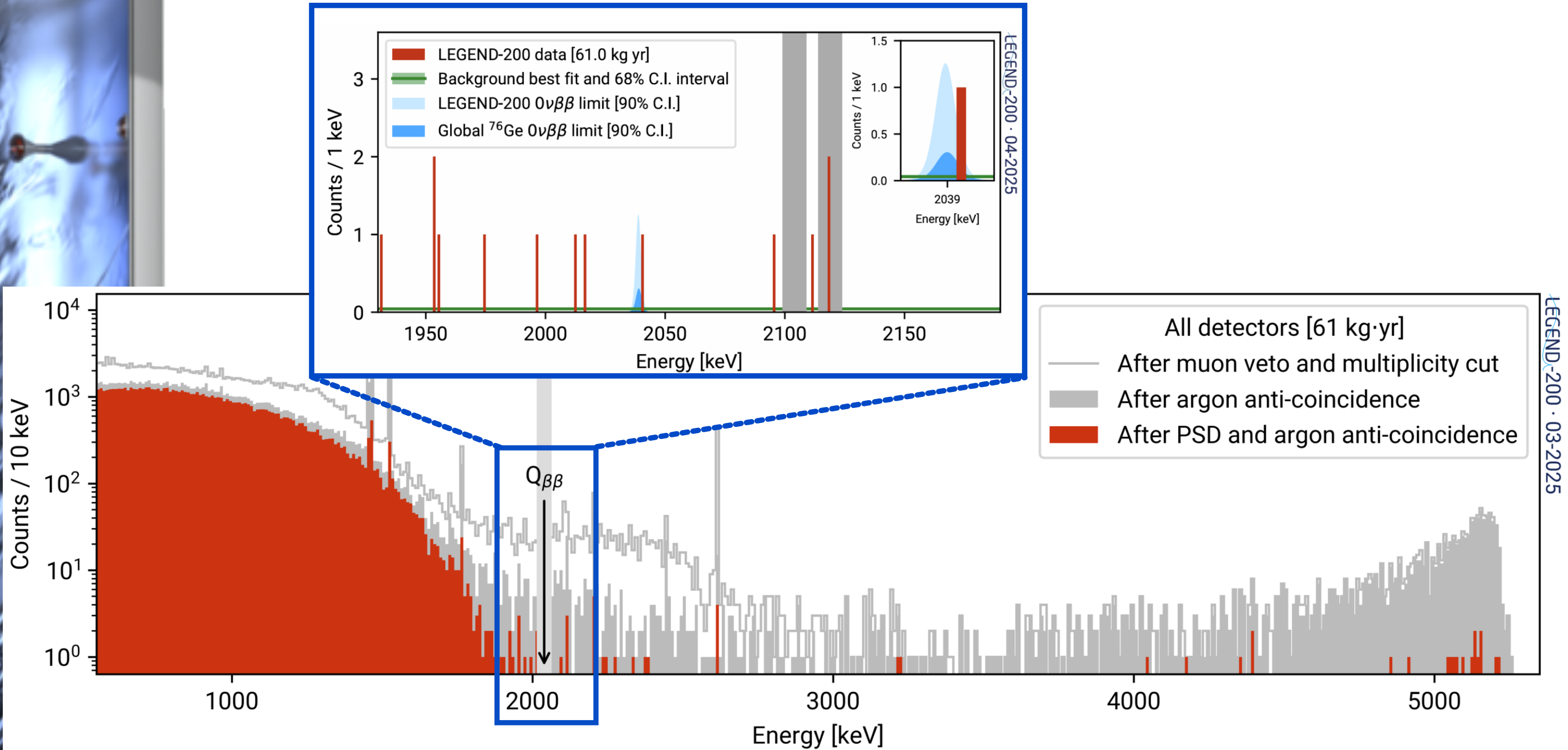
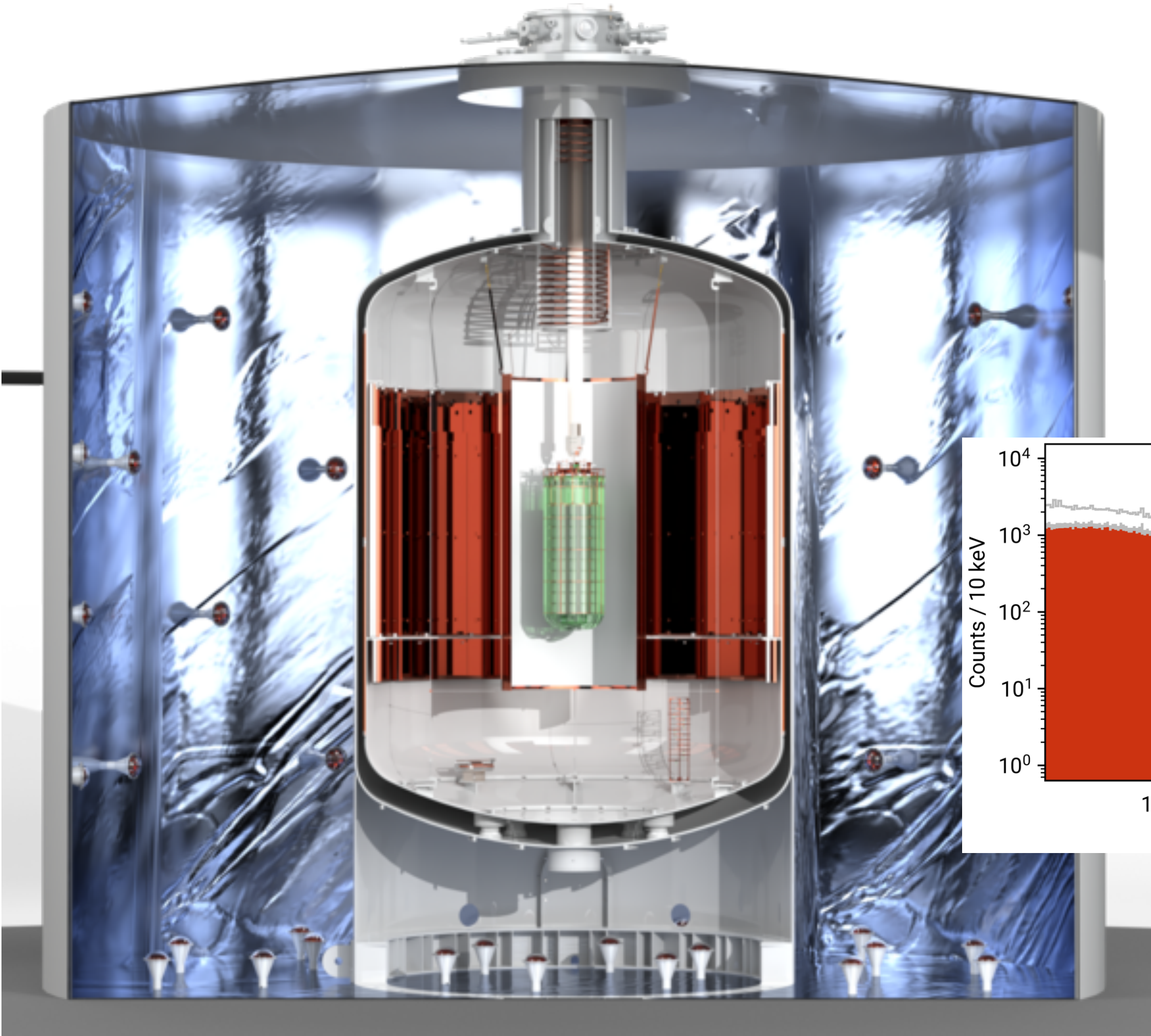
LÍMITES ACTUALES

- **KamLAND-Zen (^{136}Xe):** $T_{1/2} > 3.8 \times 10^{26}$ años (90% CL) $\rightarrow m_{\beta\beta} < 28\text{--}122$ meV
- **GERDA (^{76}Ge):** $T_{1/2} > 1.8 \times 10^{26}$ años (90% CL) $\rightarrow m_{\beta\beta} < 79\text{--}180$ meV



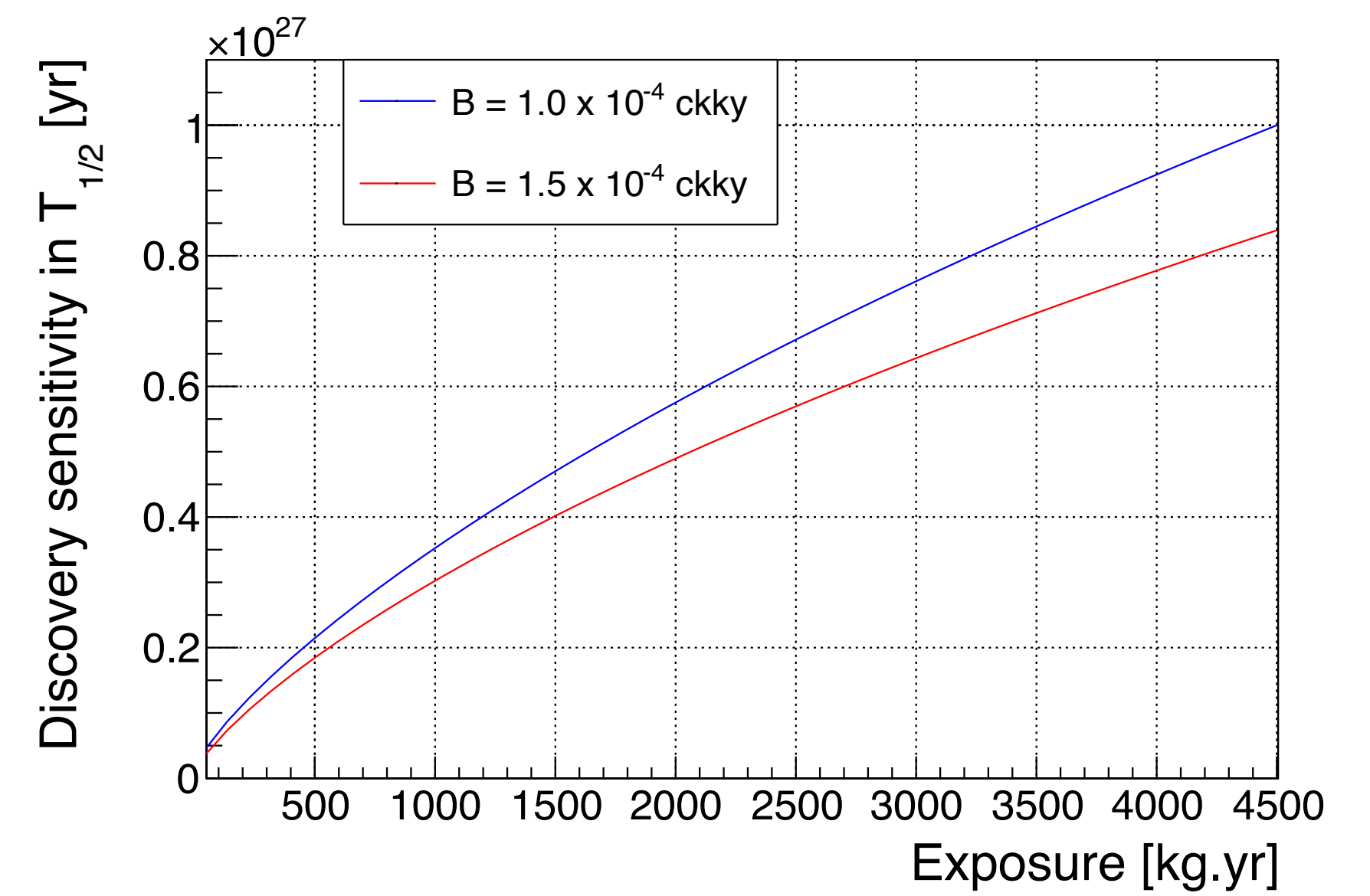
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2 \qquad m_{\beta\beta} = \sum_i |U_e^2 i| m_i$$

LEGEND-200



CUORE / CUPID

45



@next

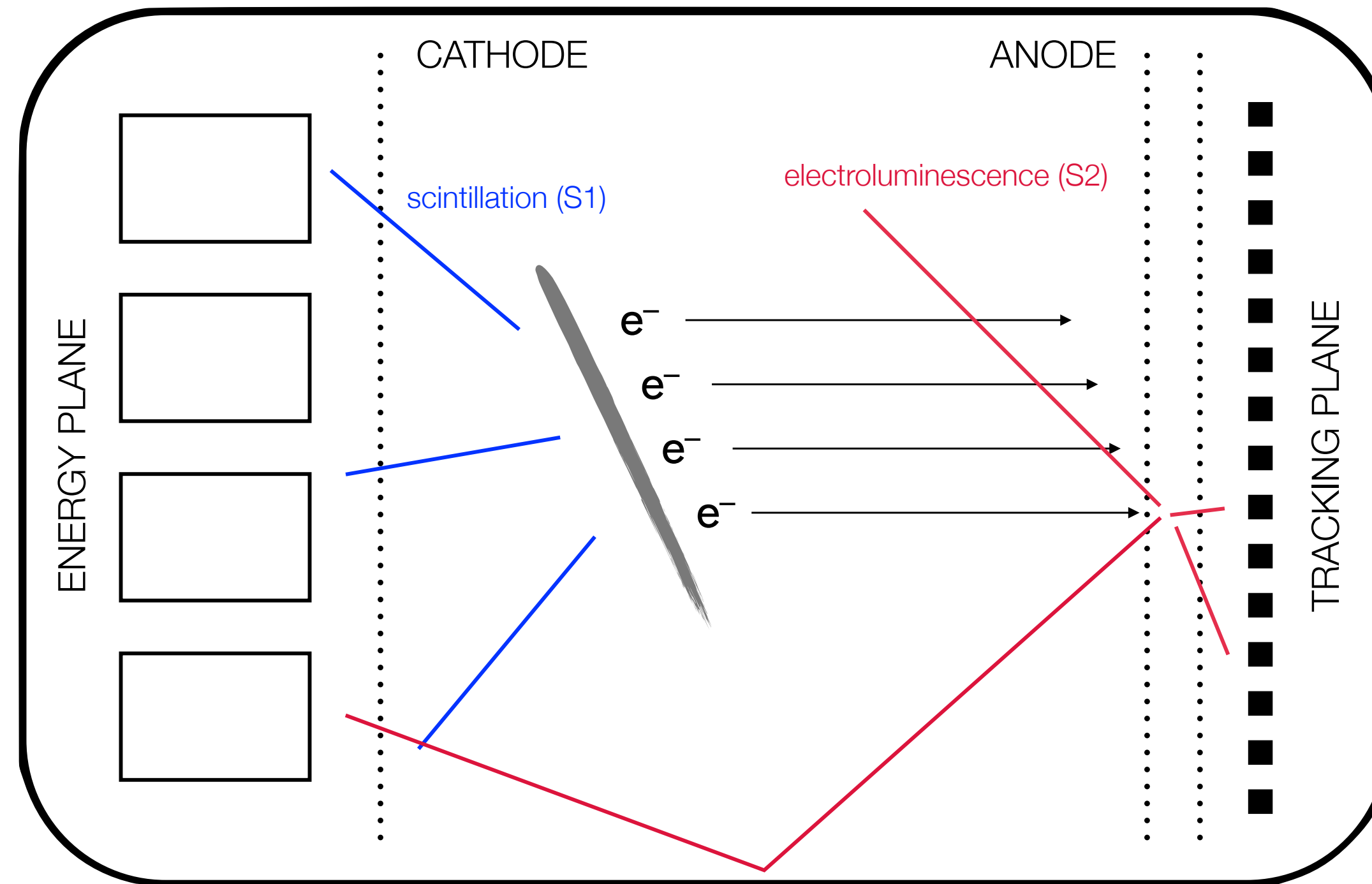


The NEXT Collaboration



Detector concept

48

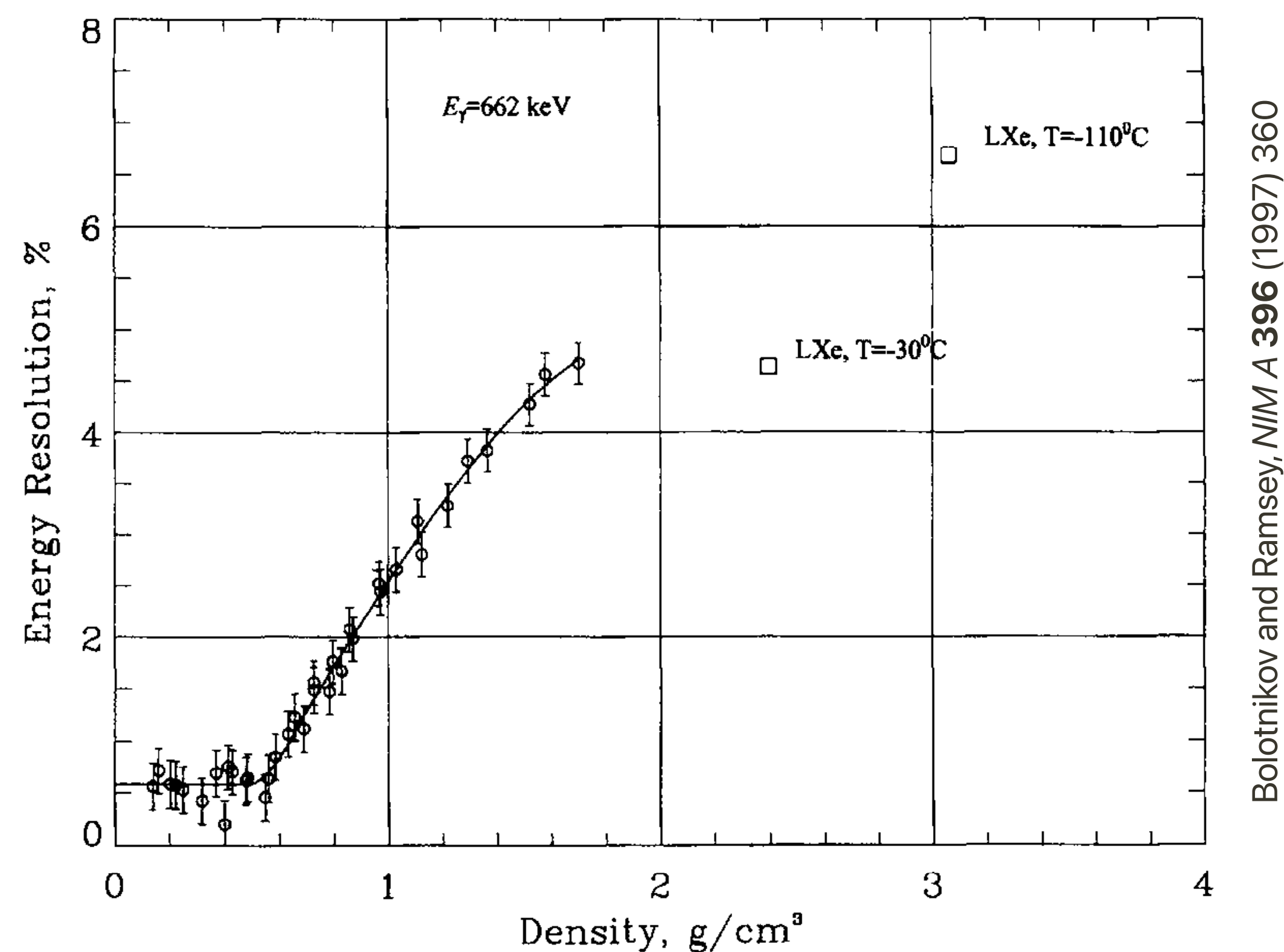


Xenon gas time projection chamber with electroluminescent amplification.

- Primary scintillation (S1) establishes the start-of-event time.
- Secondary scintillation (S2) is used for calorimetry and tracking.
- Specialised photosensor arrays for each measurement.

Energy resolution in xenon

49



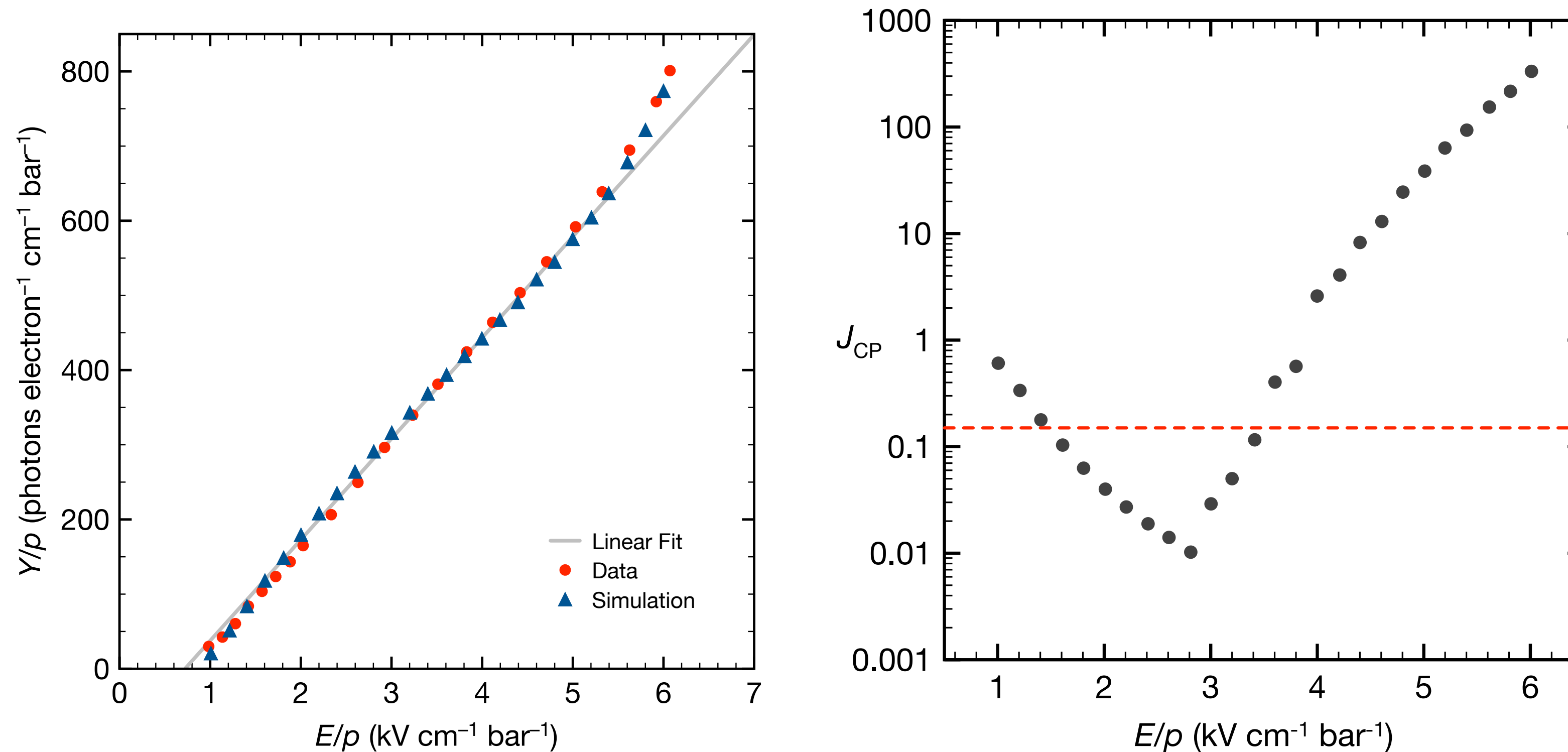
Bolotnikov and Ramsey, *NIM A* **396** (1997) 360

Intrinsic energy resolution of xenon gas close to 0.3% at 2.5 MeV.

Fano factor of xenon significantly smaller in gaseous phase than in liquid.

Electroluminescence

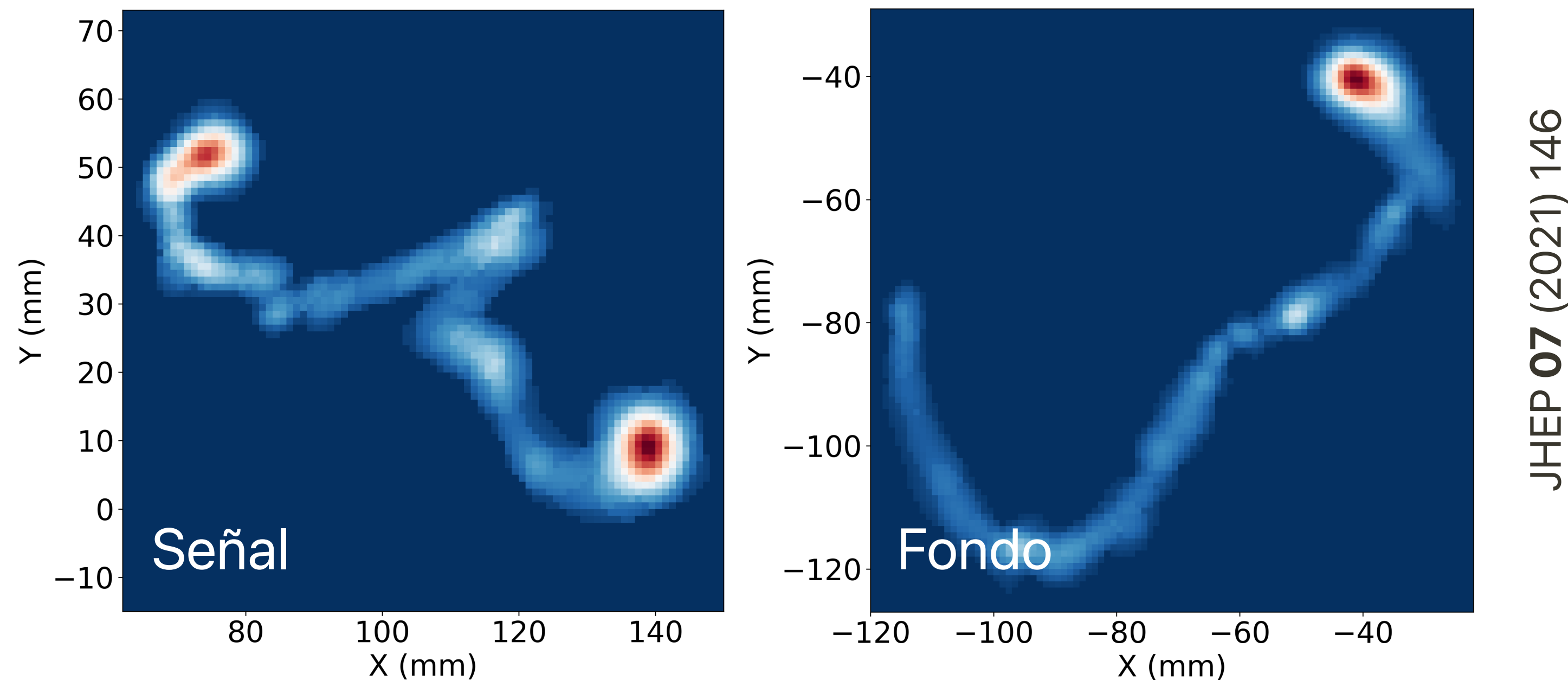
50



Emission of scintillation light by atoms excited by a charge accelerated by an electric field.
High, linear amplification gain with sub-Poisson fluctuations.

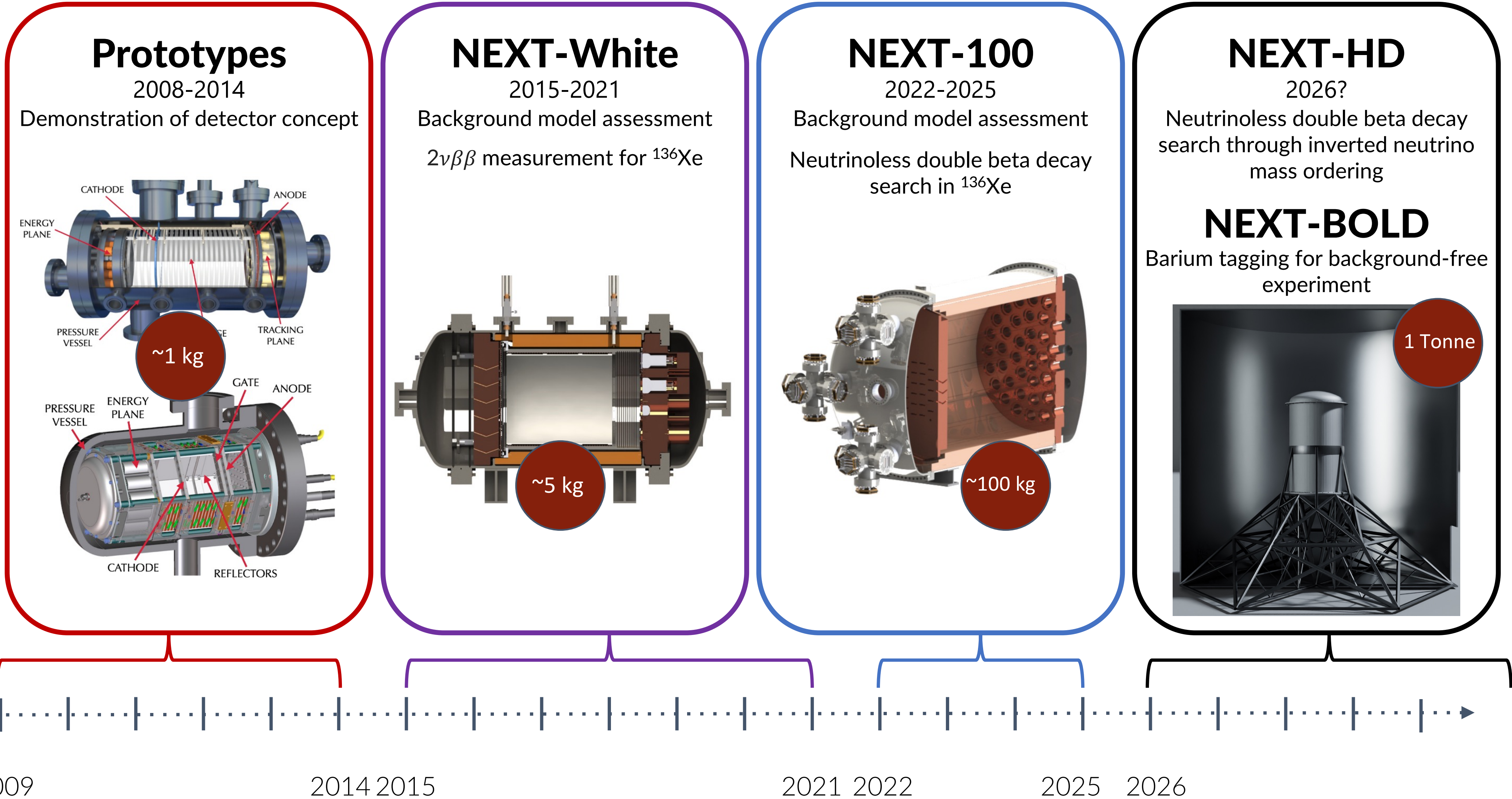
Topological event identification

51



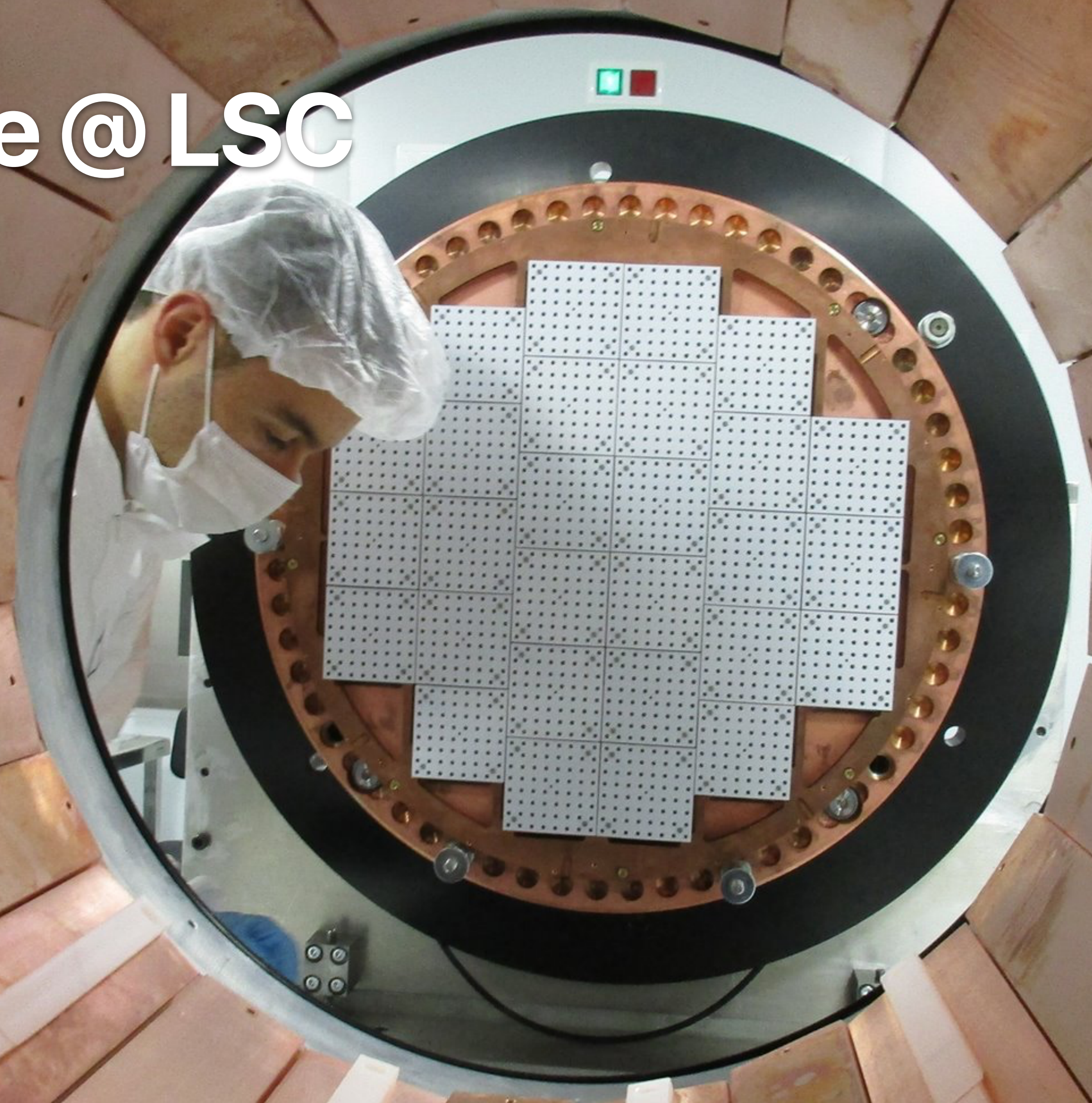
Signal events (two electron tracks with a common vertex) feature high dE/dx blobs at both ends, unlike most common background events (single electrons).

The project



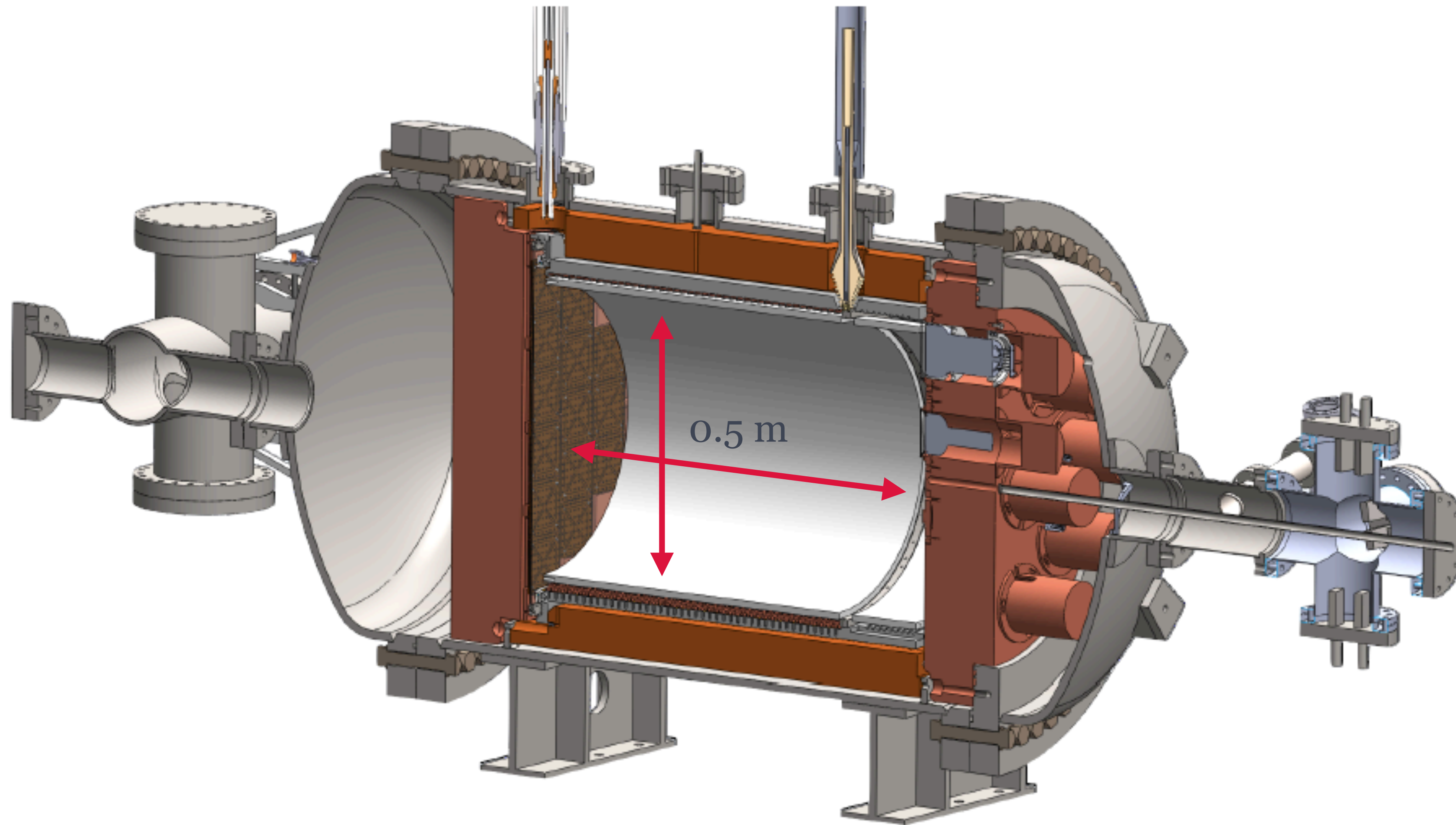
NEXT-White @ LSC

53

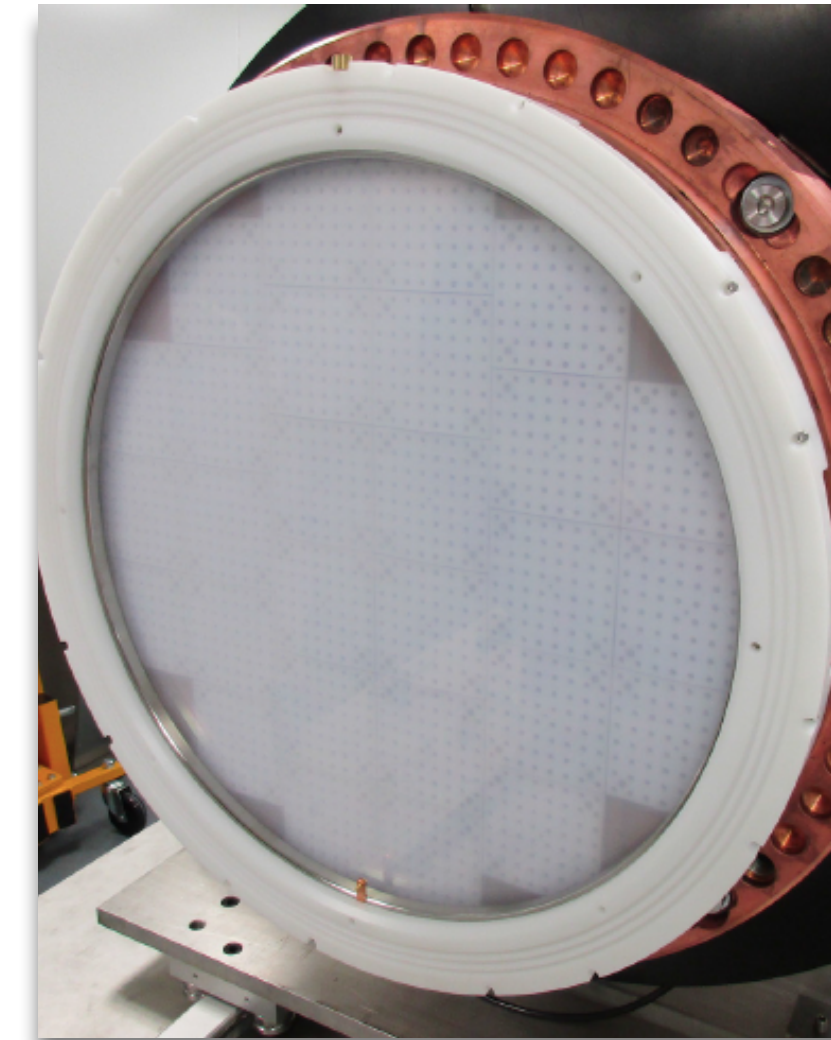
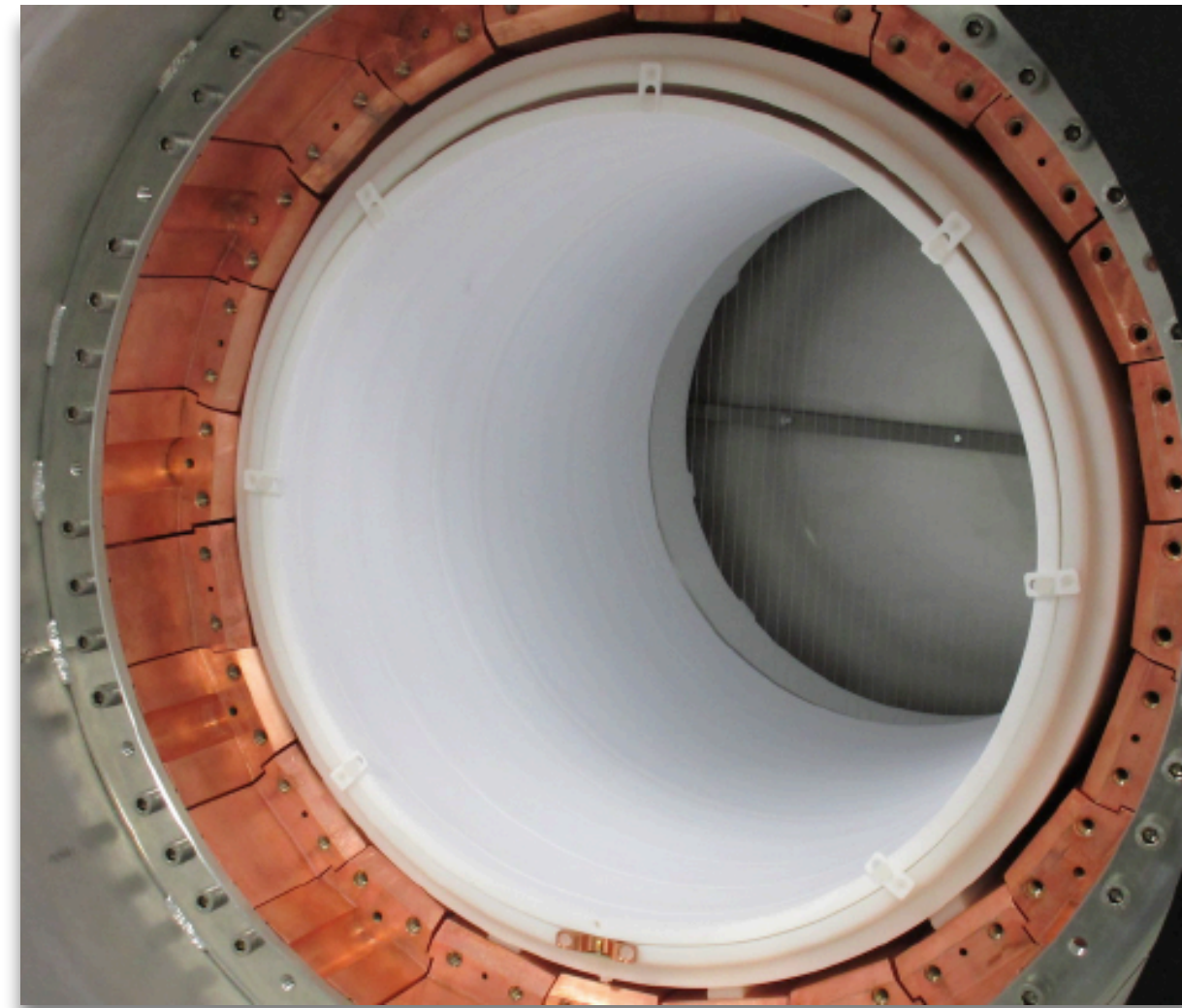


NEXT-White

54



NEXT-White



55

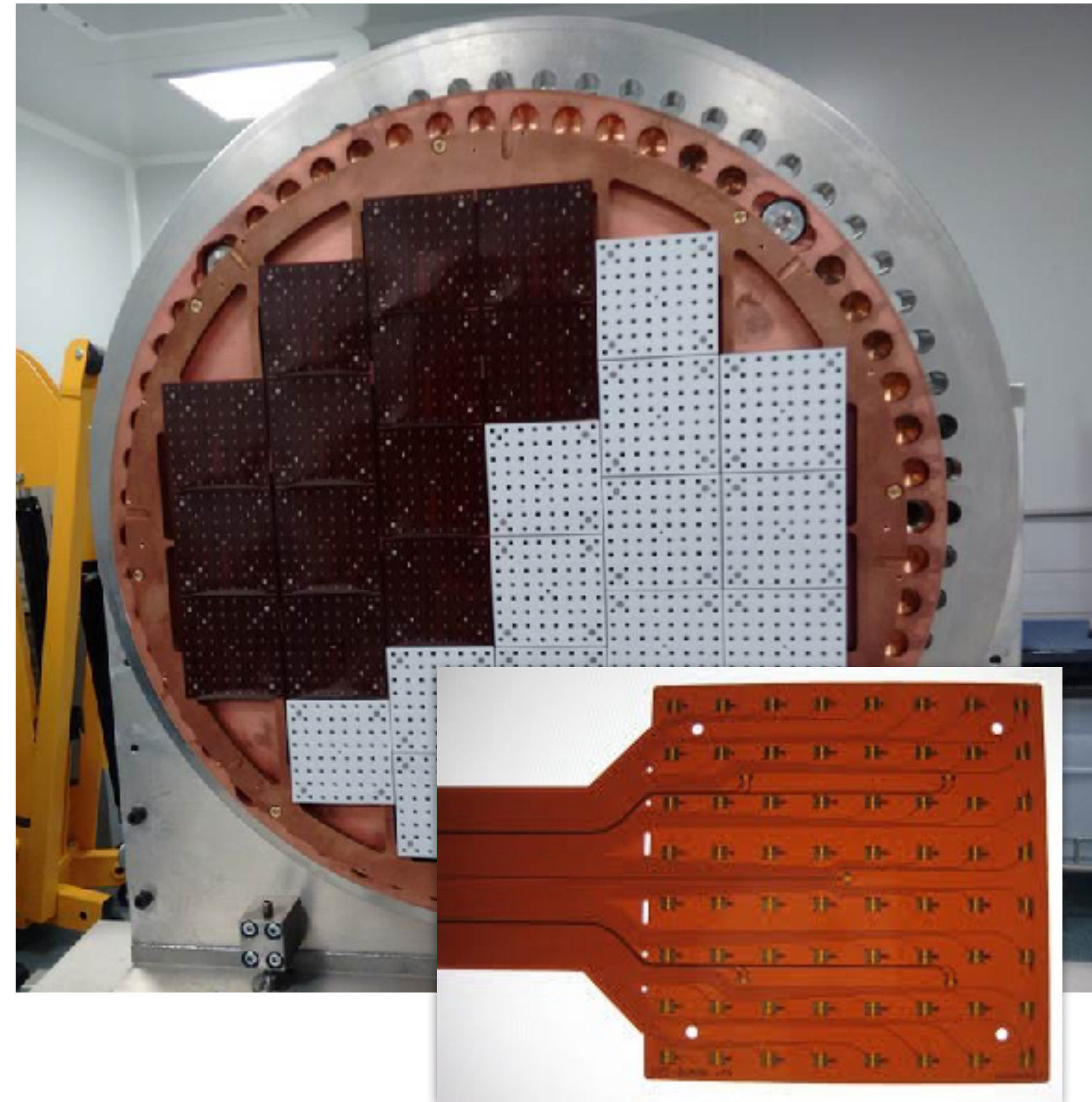


NEXT-White

56



12 Hamamatsu R11410



2000+ SensL 1-mm² SiPMs

NEXT-White

57



NEXT-White

58

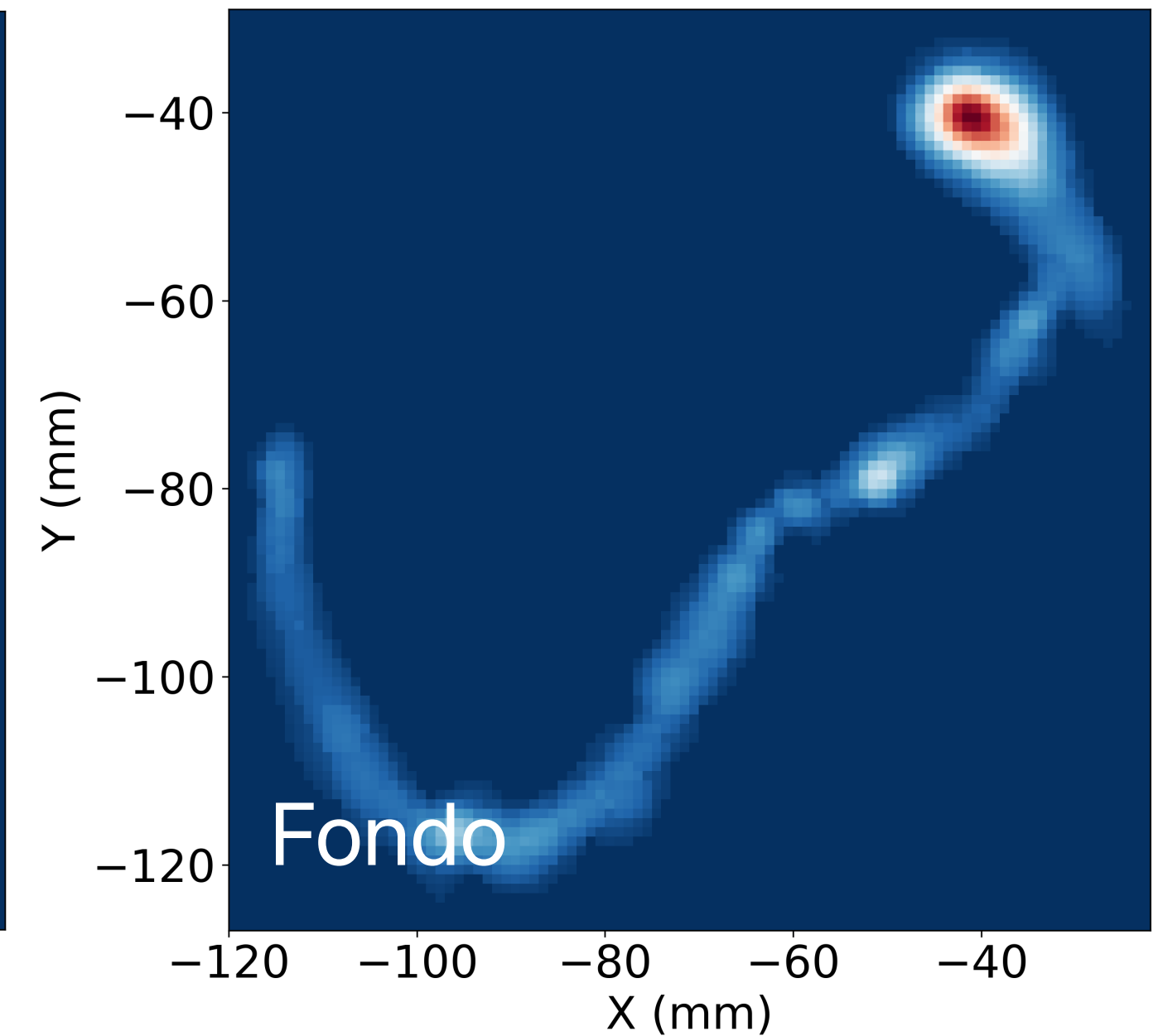
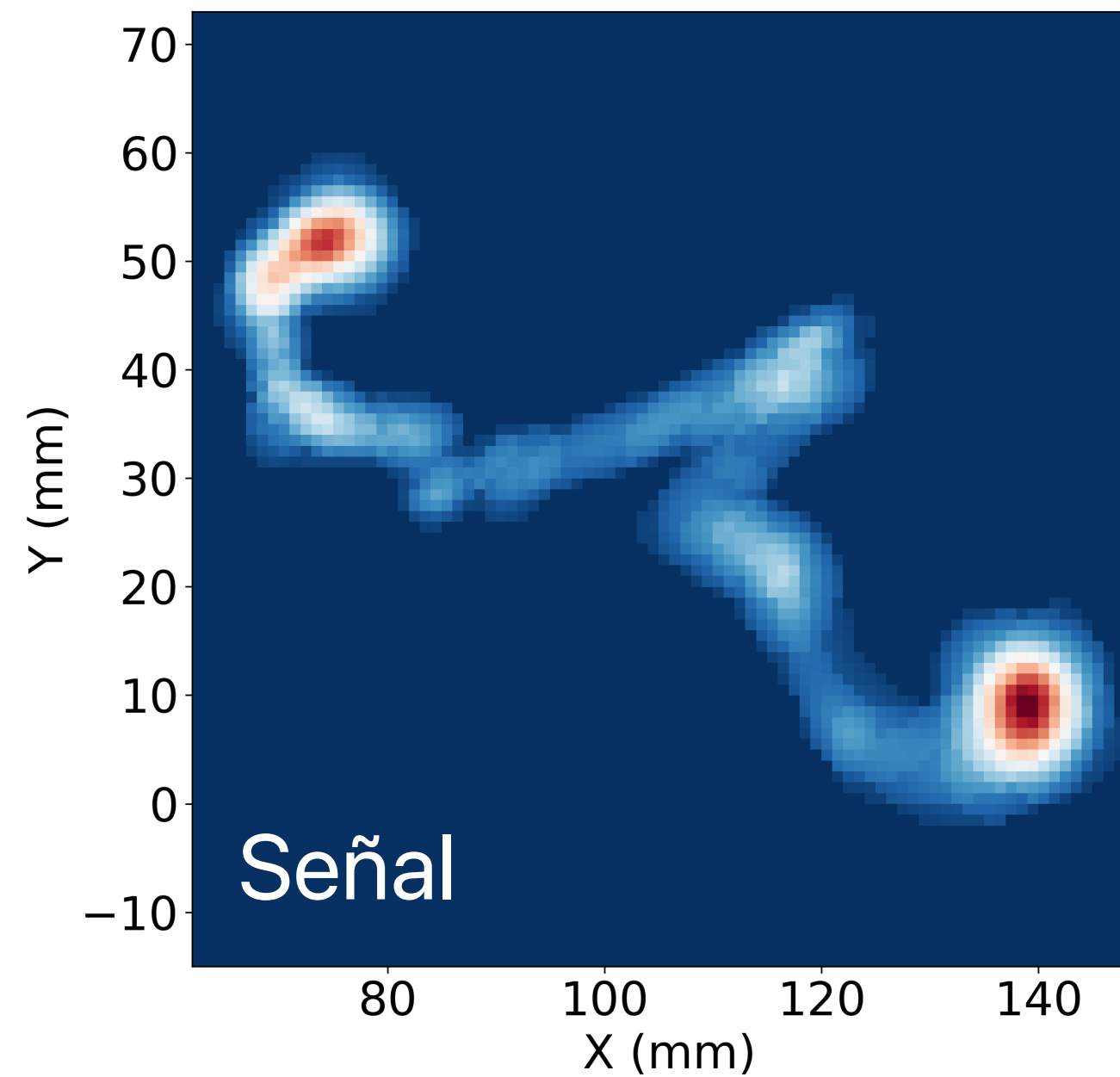
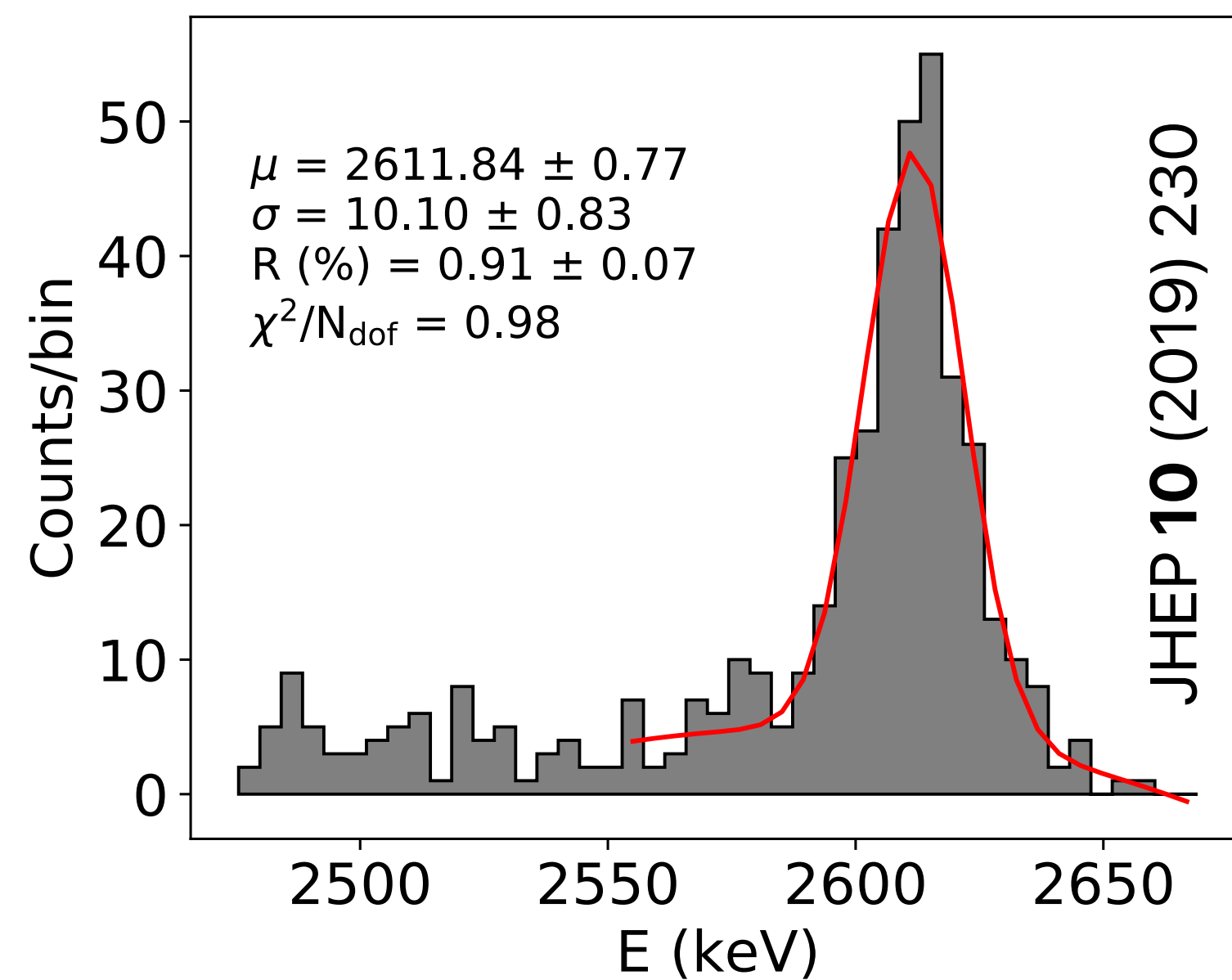


The NEXT-White setup in Hall A at the Laboratorio Subterráneo de Canfranc.

EL EXPERIMENTO NEXT: RESULTADOS (1)

59

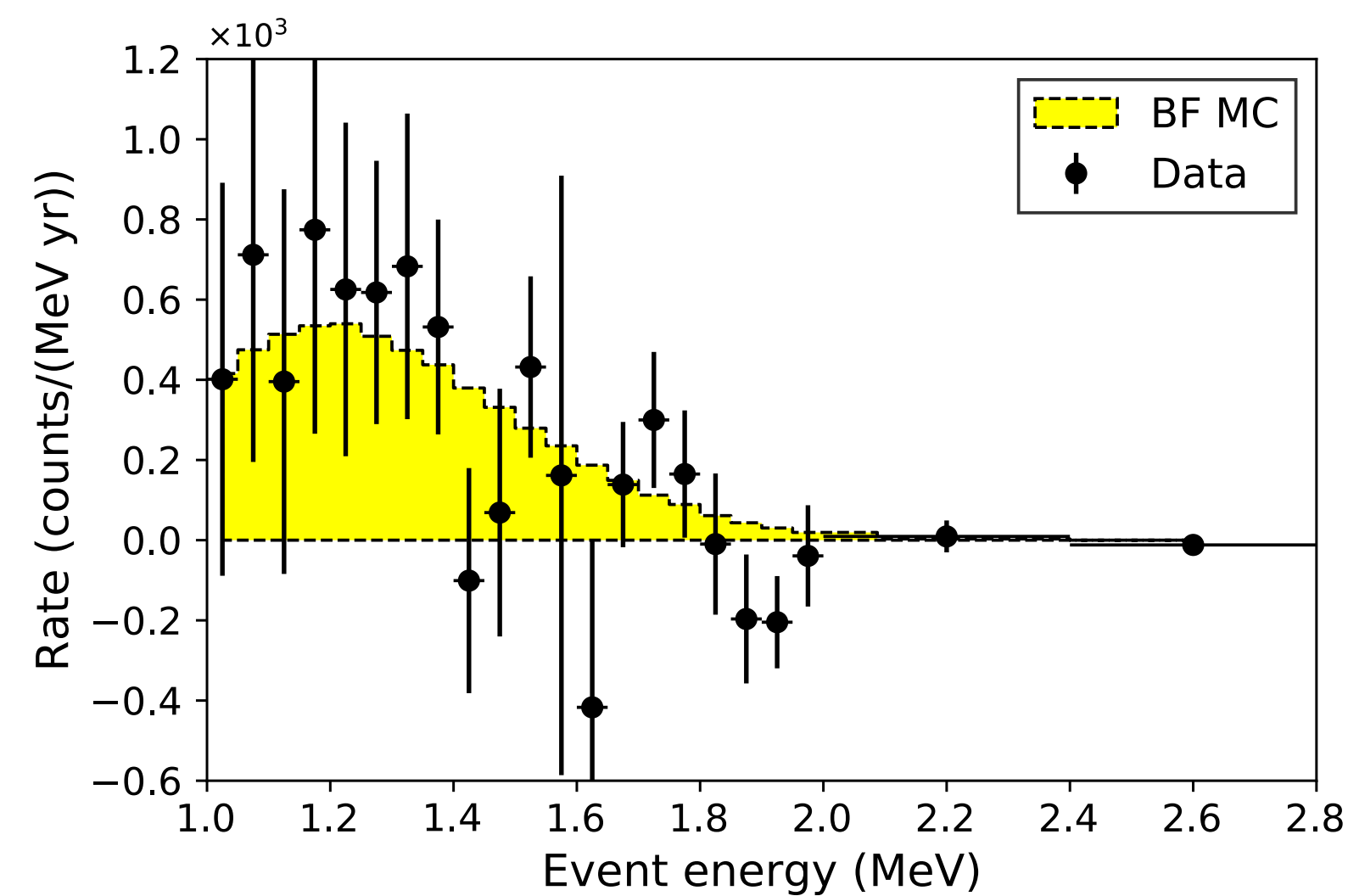
- **Resolución energética** (medida a diferentes energías) extrapolable a **<1% FWHM a 2.5 MeV**.
- **Reconstrucción de trazas eficaz** para distinguir eventos con 1 o 2 electrones.



JHEP **07** (2021) 146

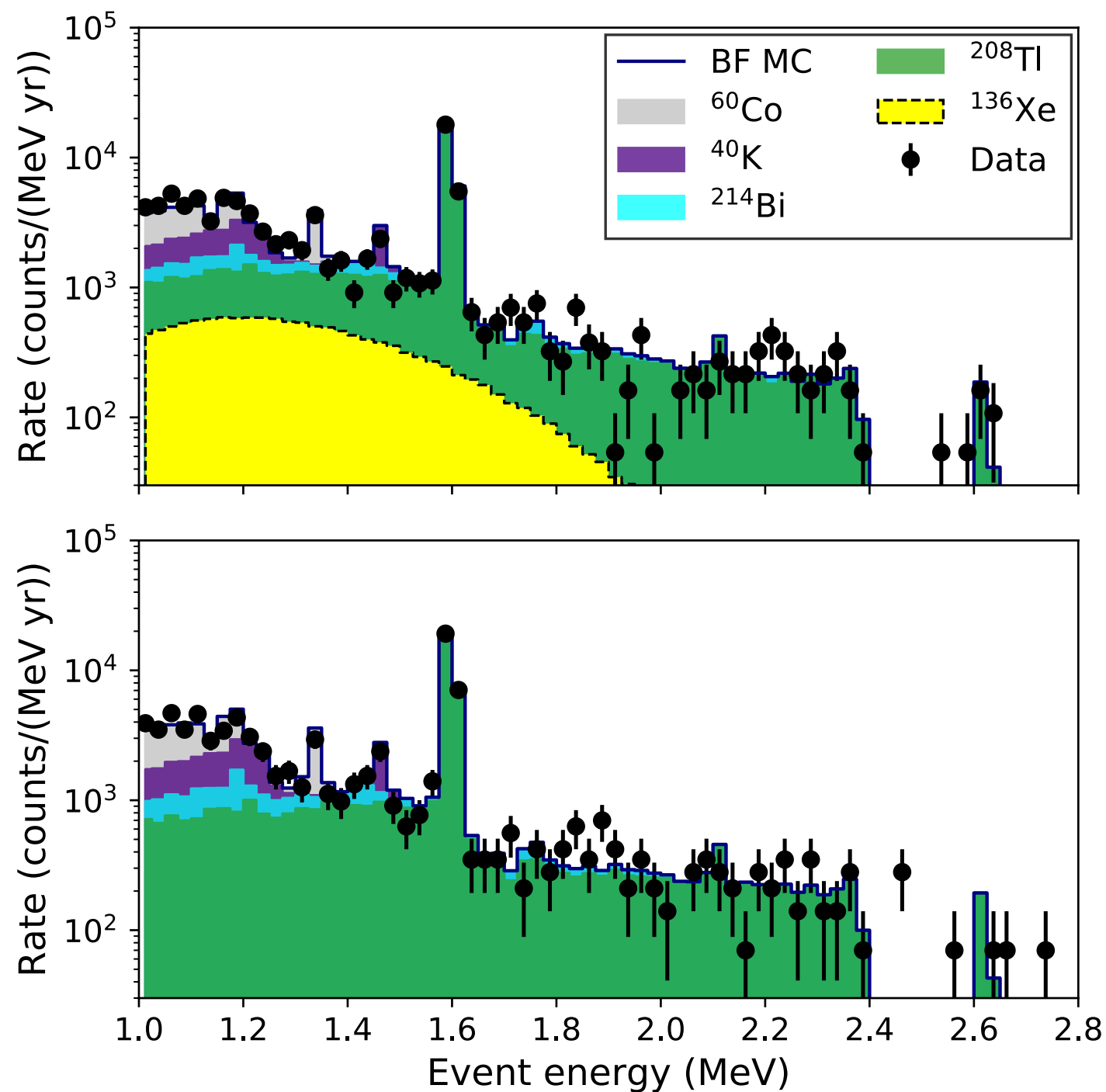
EL EXPERIMENTO NEXT: RESULTADOS (2)

- **Medida de la semivida de la desintegración $2\nu\beta\beta$ del ^{136}Xe en NEXT-White usando dos métodos de análisis diferentes:**
 - Sustracción de los espectros medidos con xenón enriquecido y con xenón empobrecido en ^{136}Xe .
 - Ajuste de los datos al modelo de fondo del experimento.



$$T_{1/2} = 2.34^{+0.80}_{-0.46} \text{ (stat)} \text{ } ^{+0.30}_{-0.17} \text{ (sys)} \times 10^{21} \text{ yr}$$

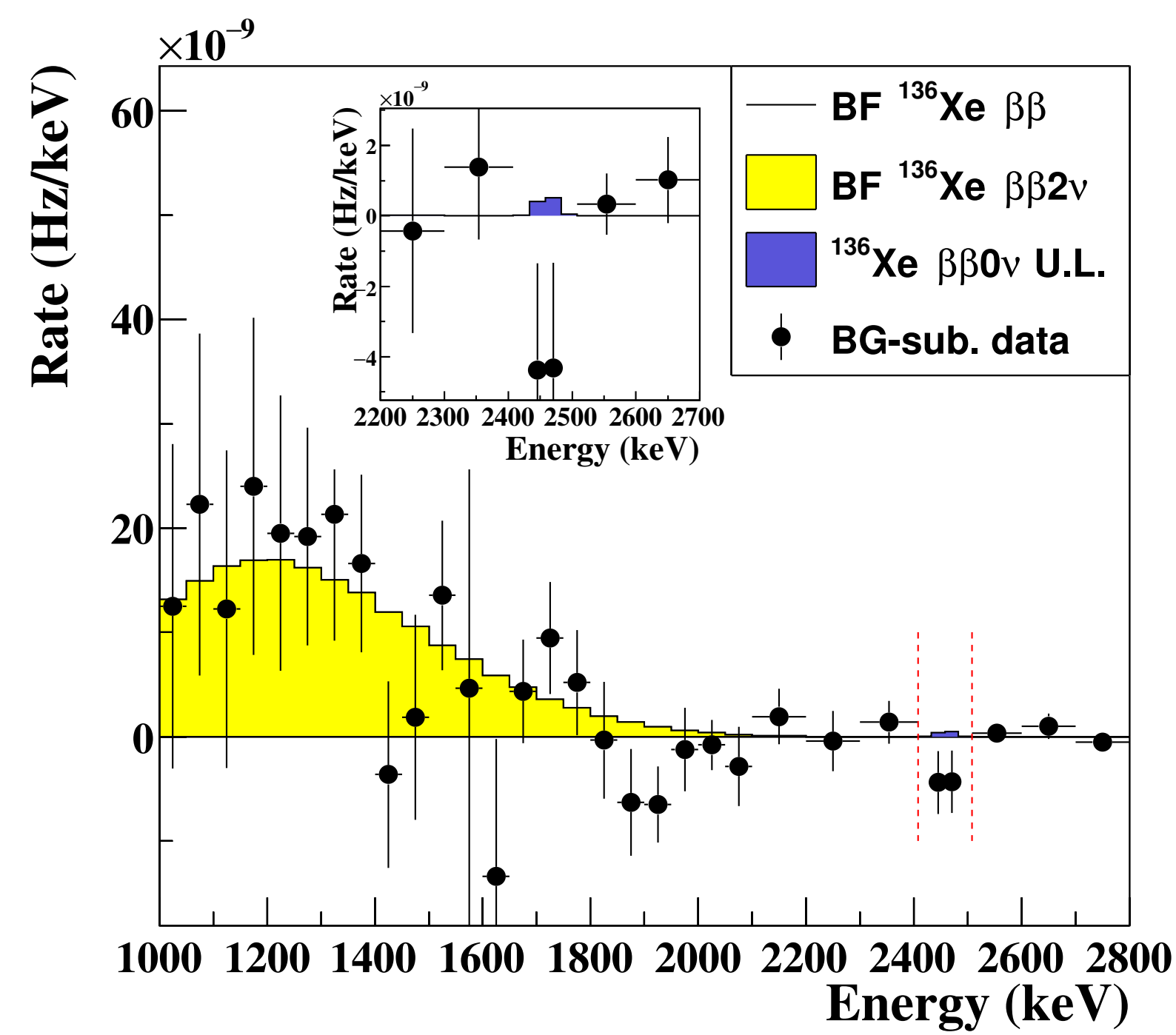
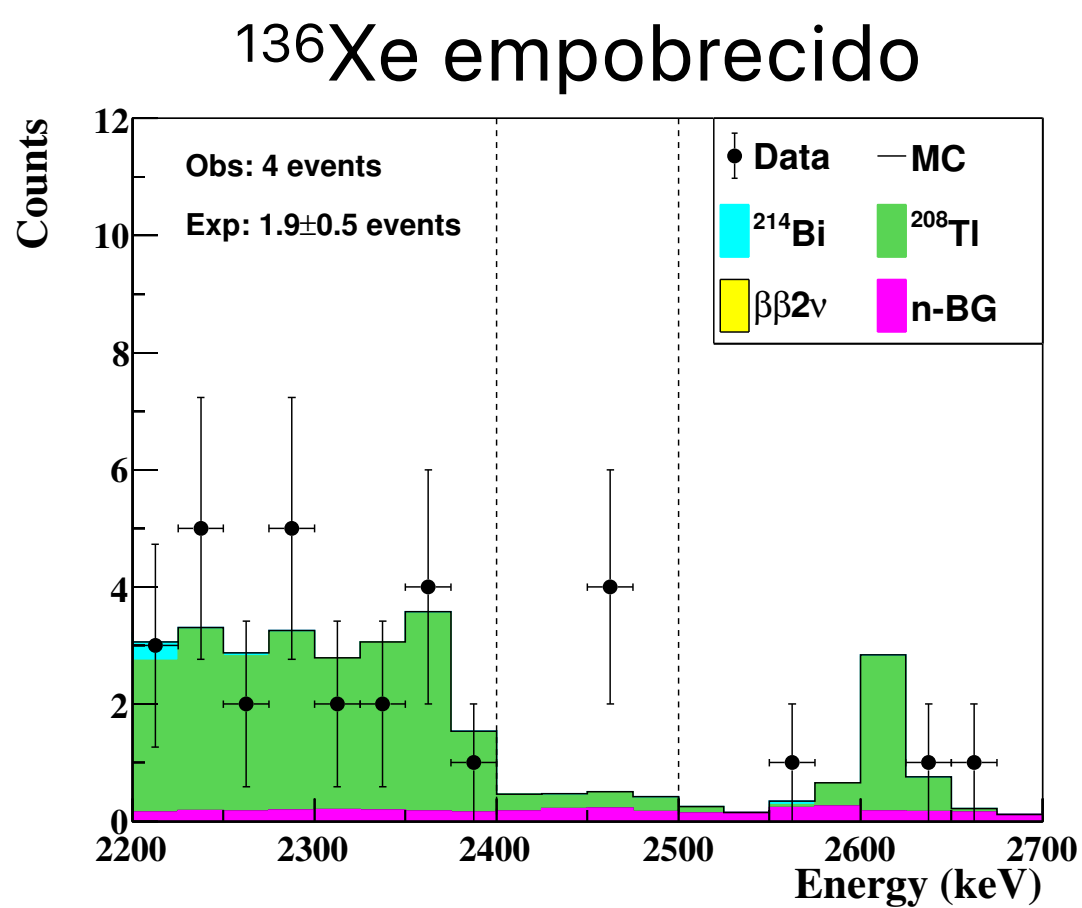
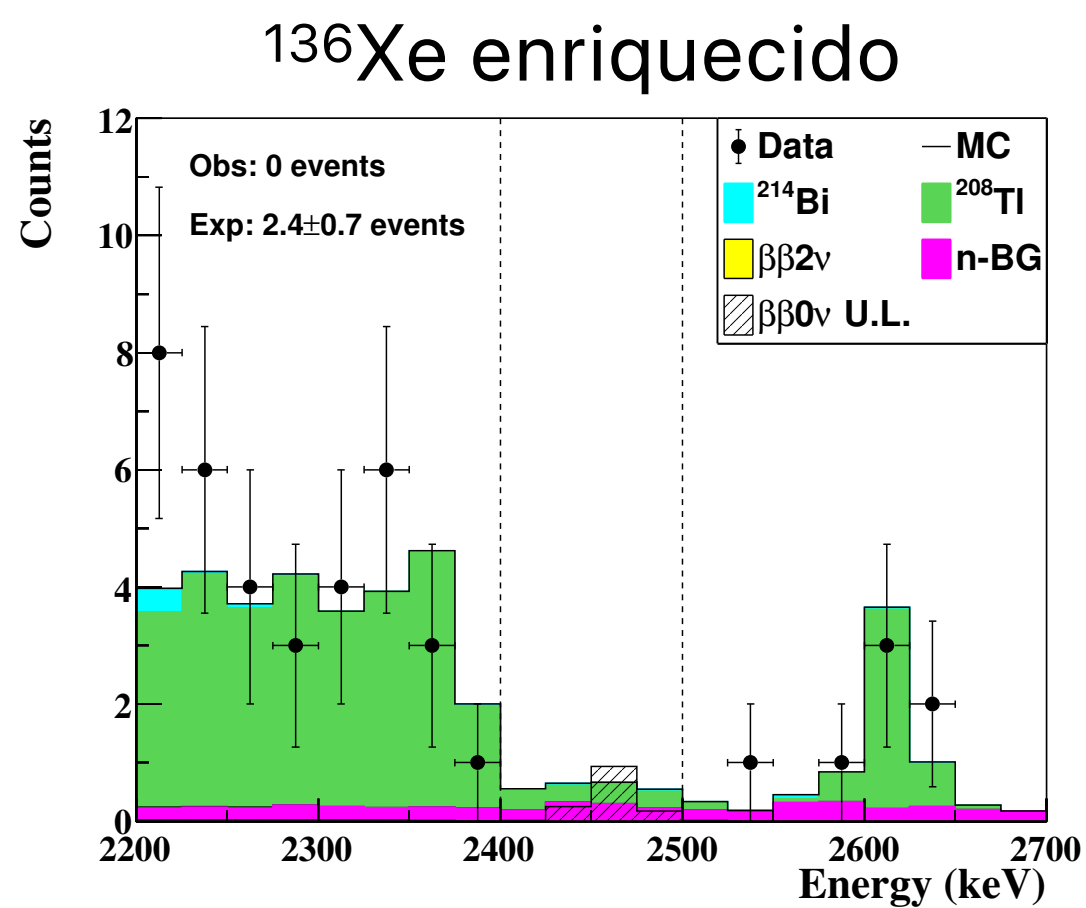
Phys. Rev. C **105** (2022) 5, 055501



Phys. Rev. C **105** (2022) 5, 055501

EL EXPERIMENTO NEXT: RESULTADOS (y 3)

- Búsqueda de la desintegración $0\nu\beta\beta$ del ^{136}Xe en NEXT-White.
 - Dada la baja exposición, el resultado no es competitivo con los mejores límites actuales, pero demuestra las capacidades de búsqueda de la tecnología.



Ajuste al modelo de fondo: $T_{1/2}^{0\nu} > 5.5 \times 10^{23}$ yr

Sustracción de fondo: $T_{1/2}^{0\nu} > 1.3 \times 10^{24}$ yr

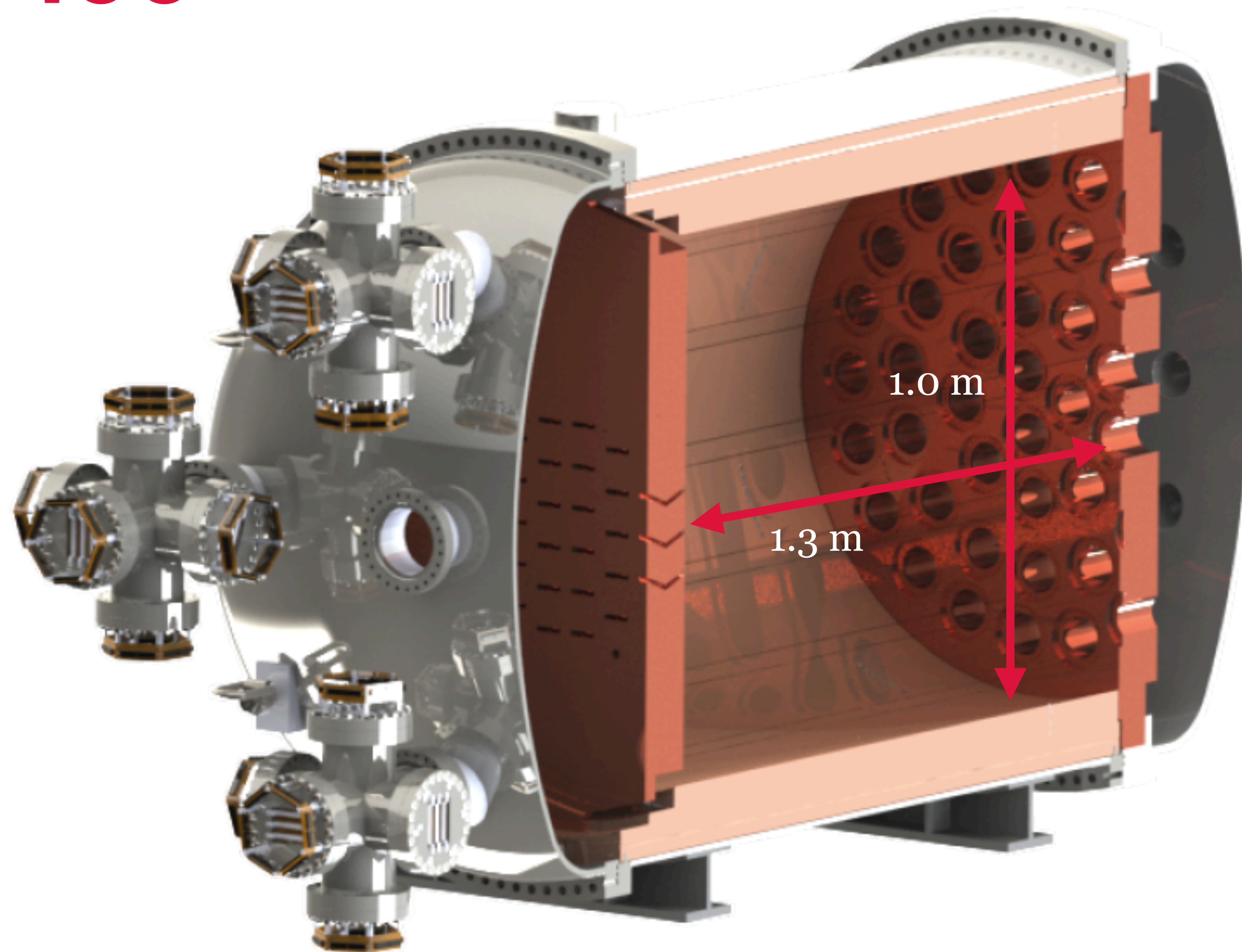
NEXT-100

62



NEXT-100

63



NEXT-100

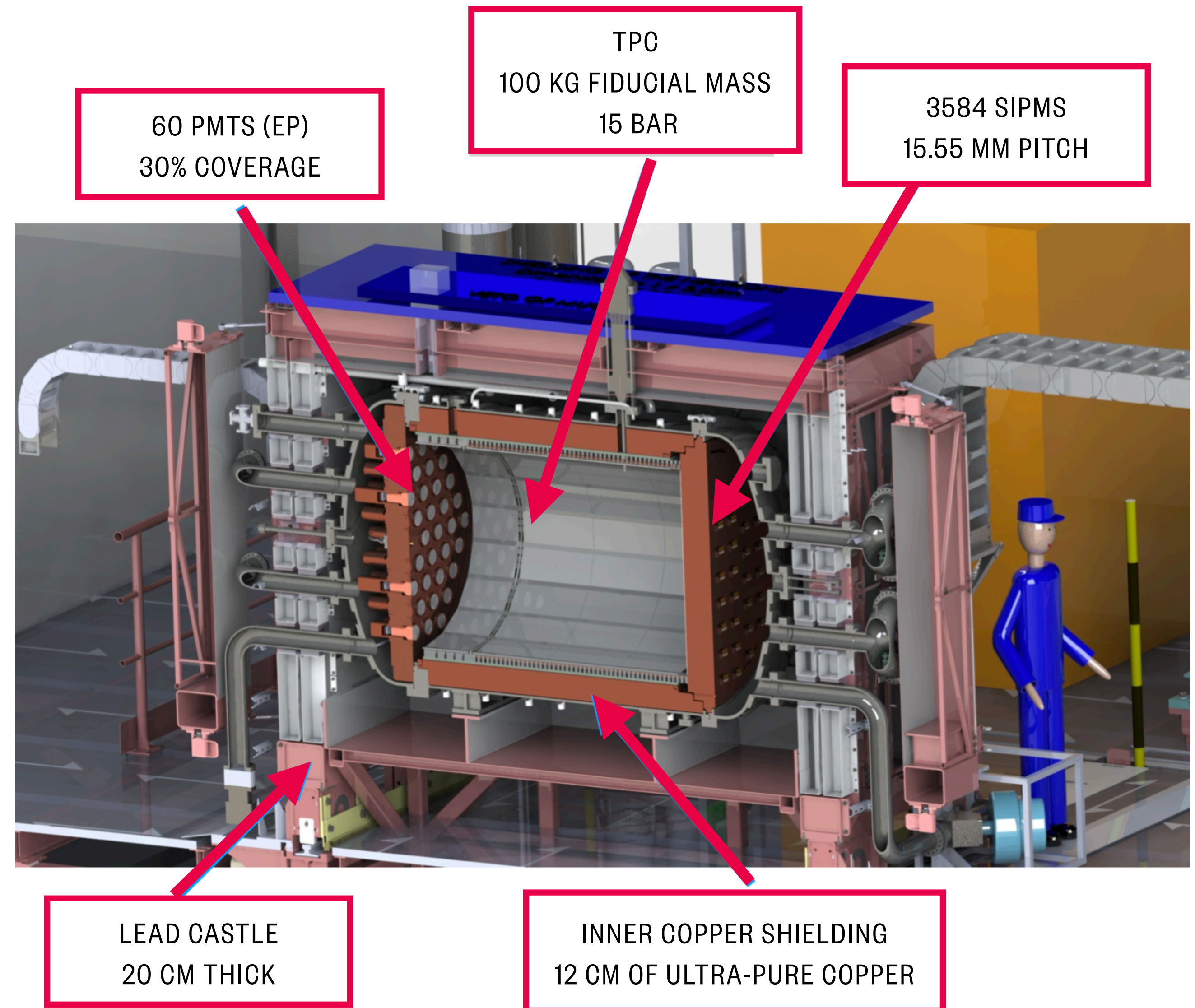
64

Scales up NEXT-White 2:1 in dimensions

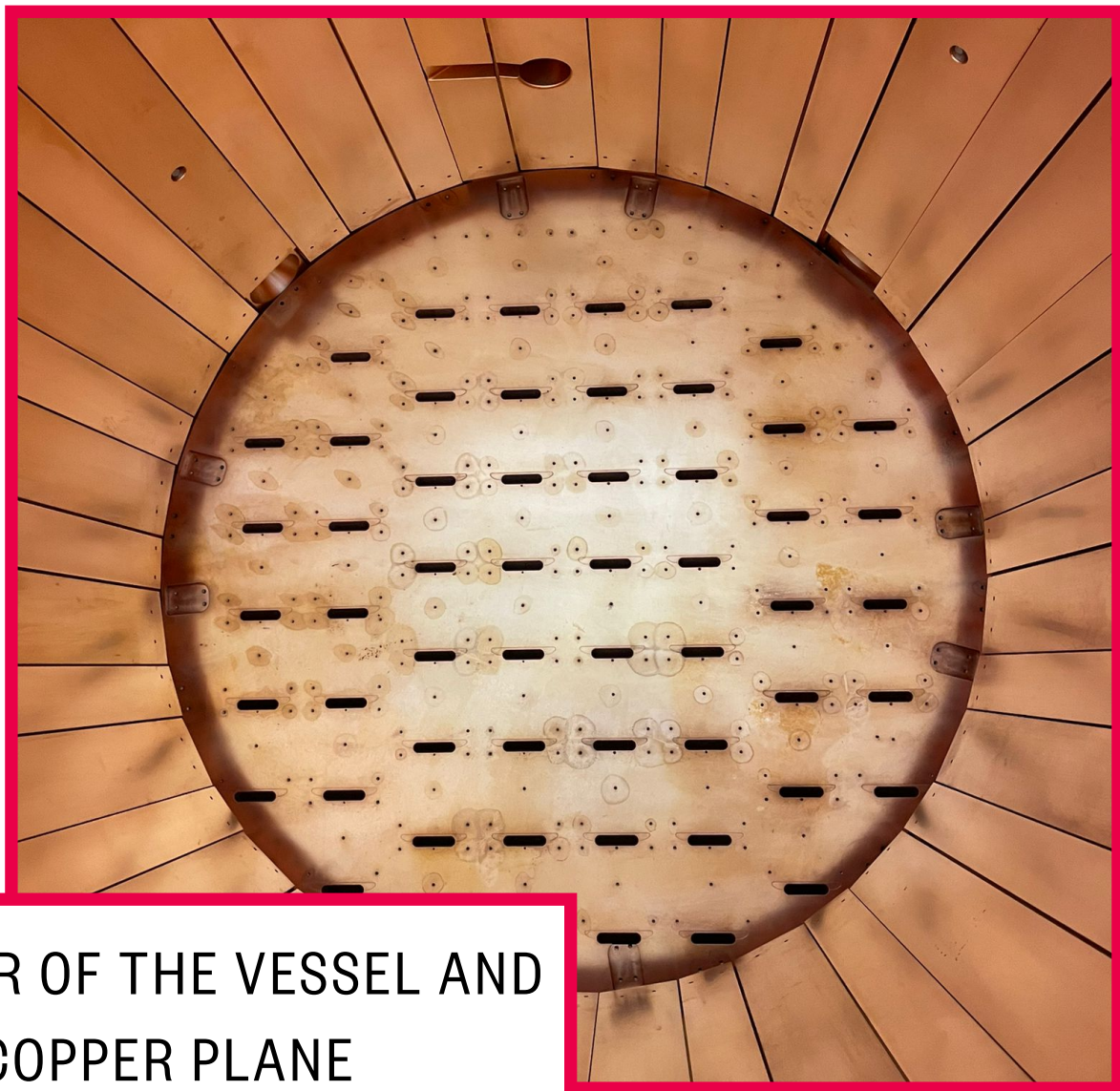
Last few weeks of construction and assembly at the LSC. Commissioning and calibration will start in January 2024.

Goals:

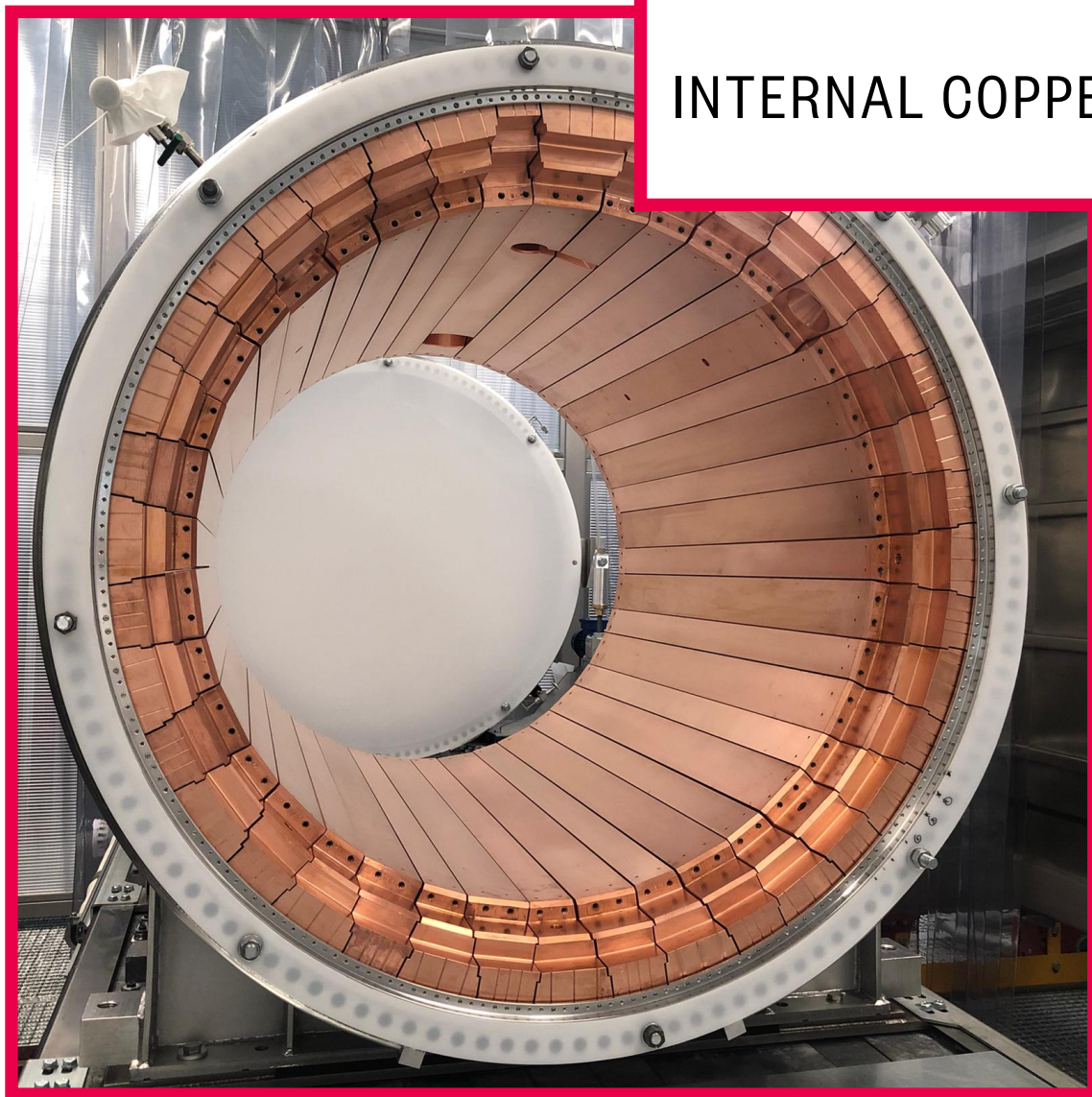
- Improve energy resolution.
- Target background rate: 1 count / year.
- Prepare for the tonne scale.



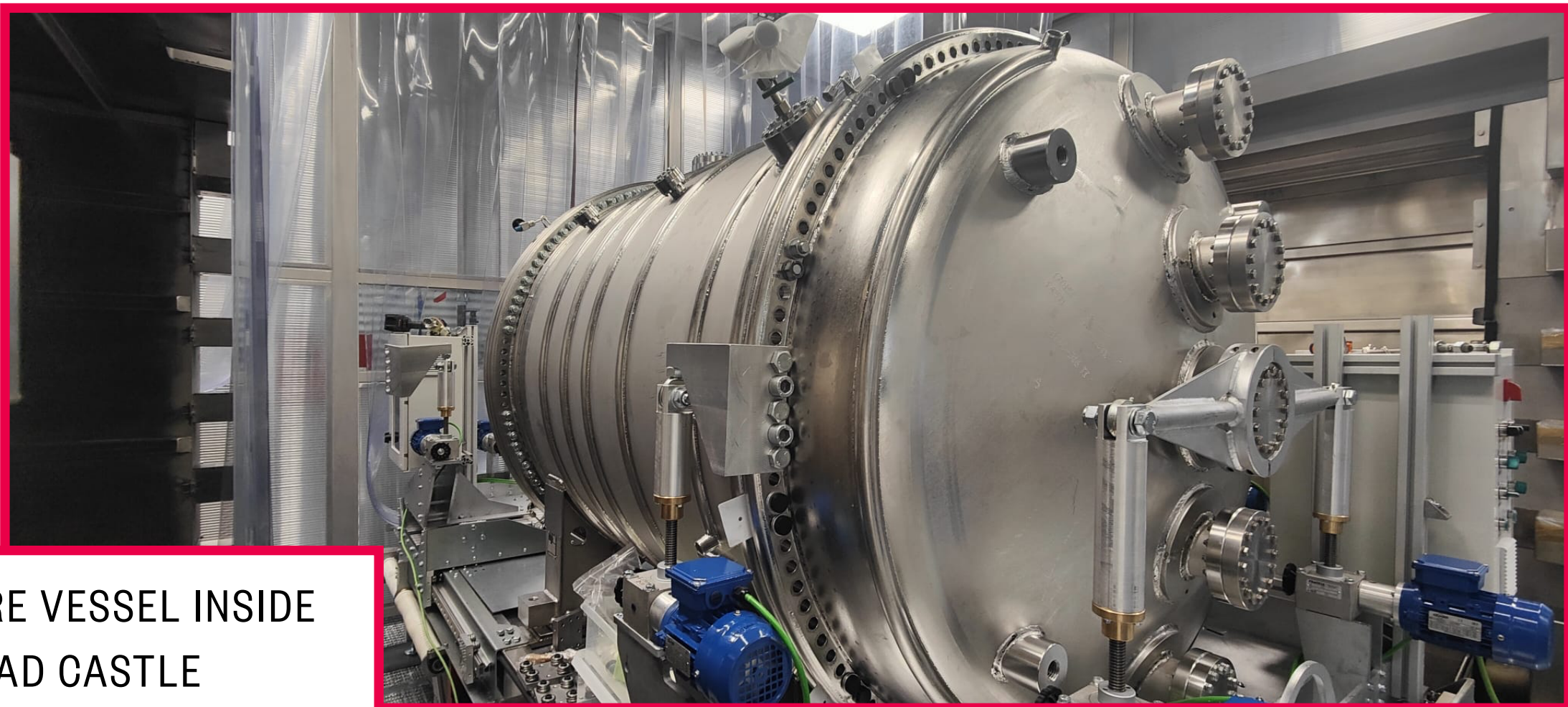
NEXT-100



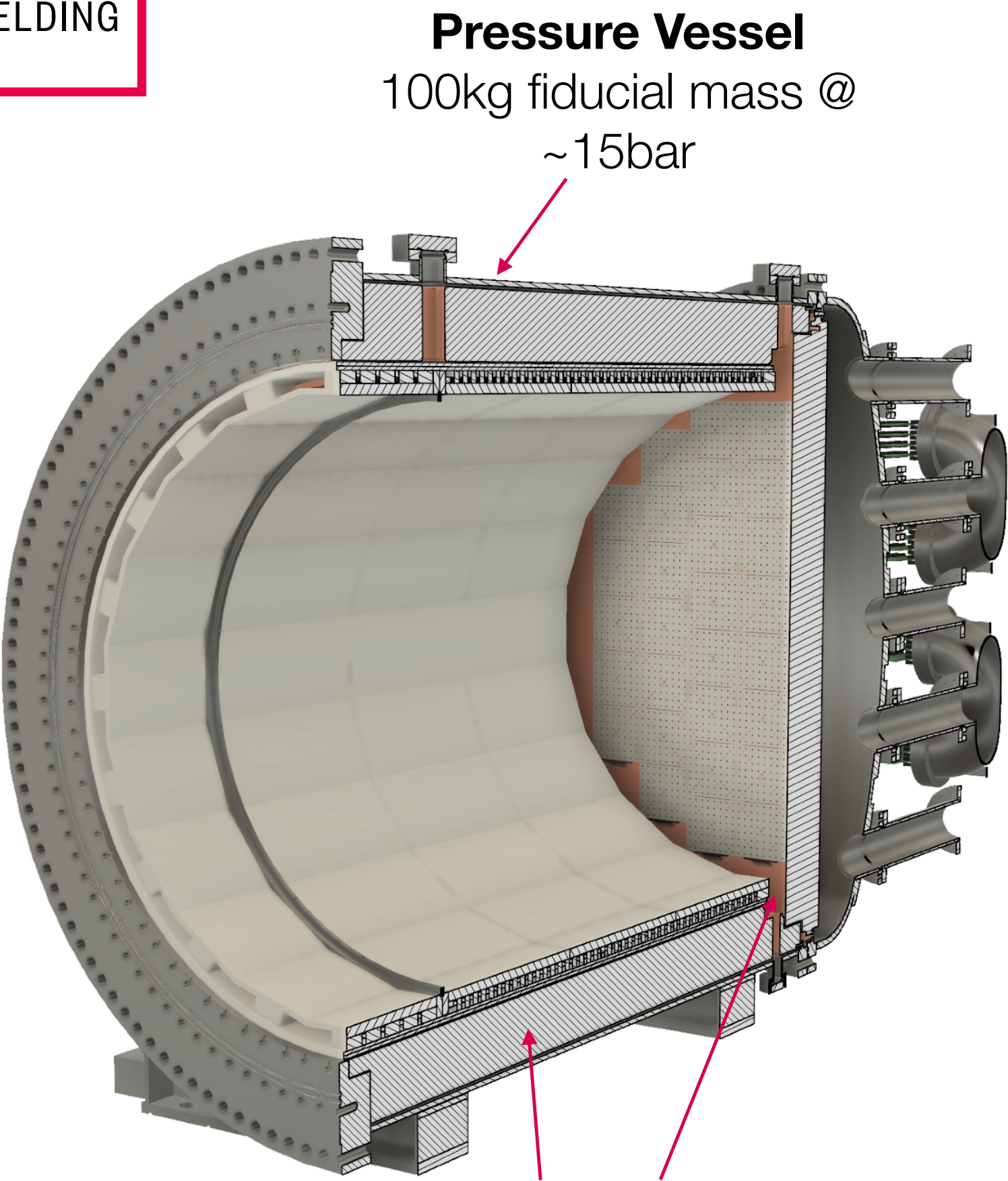
INTERIOR OF THE VESSEL AND
COPPER PLANE



INTERNAL COPPER SHIELDING



PRESSURE VESSEL INSIDE
LEAD CASTLE



Pressure Vessel
100kg fiducial mass @
~15bar

Copper Shielding

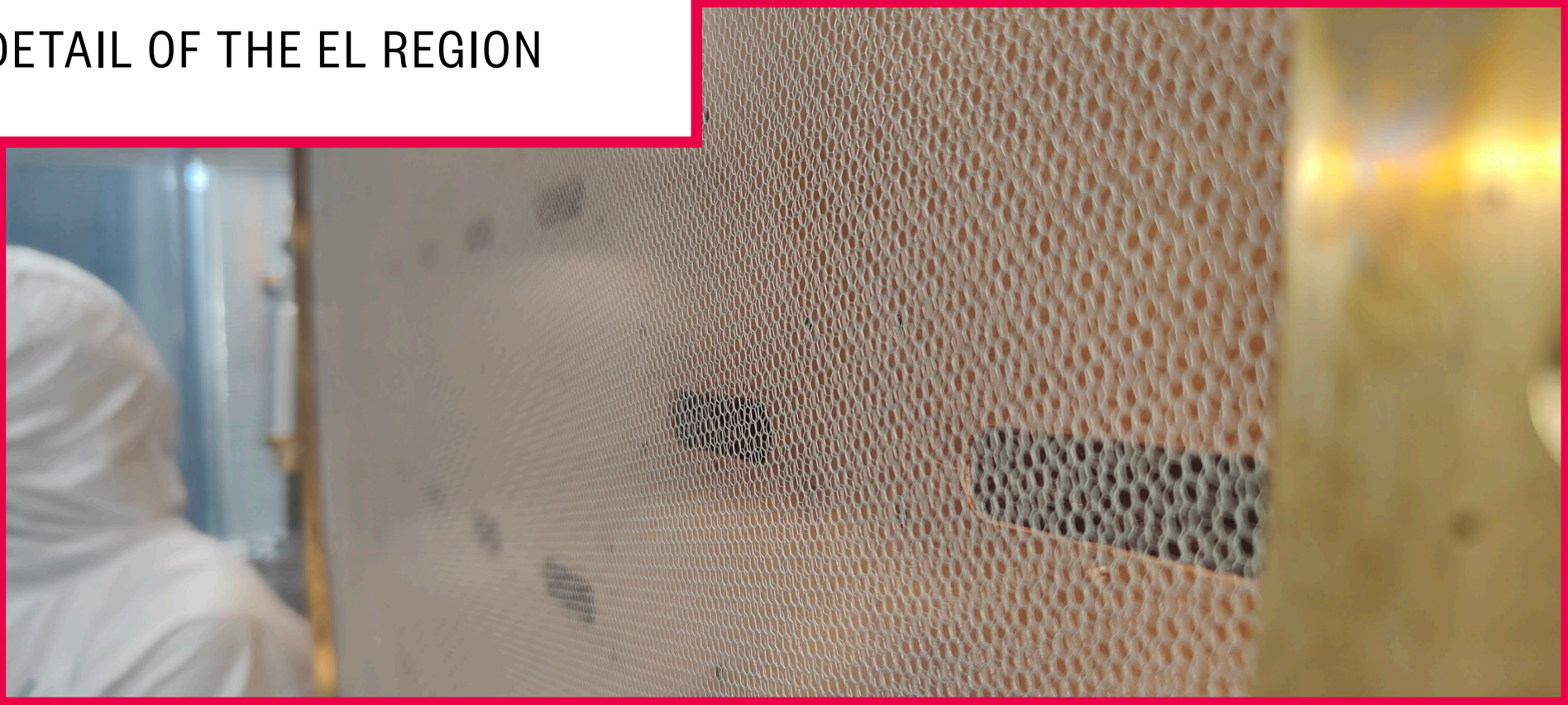
Thicker (12cm) ultra-pure copper shielding
Big machinery for production

NEXT-100

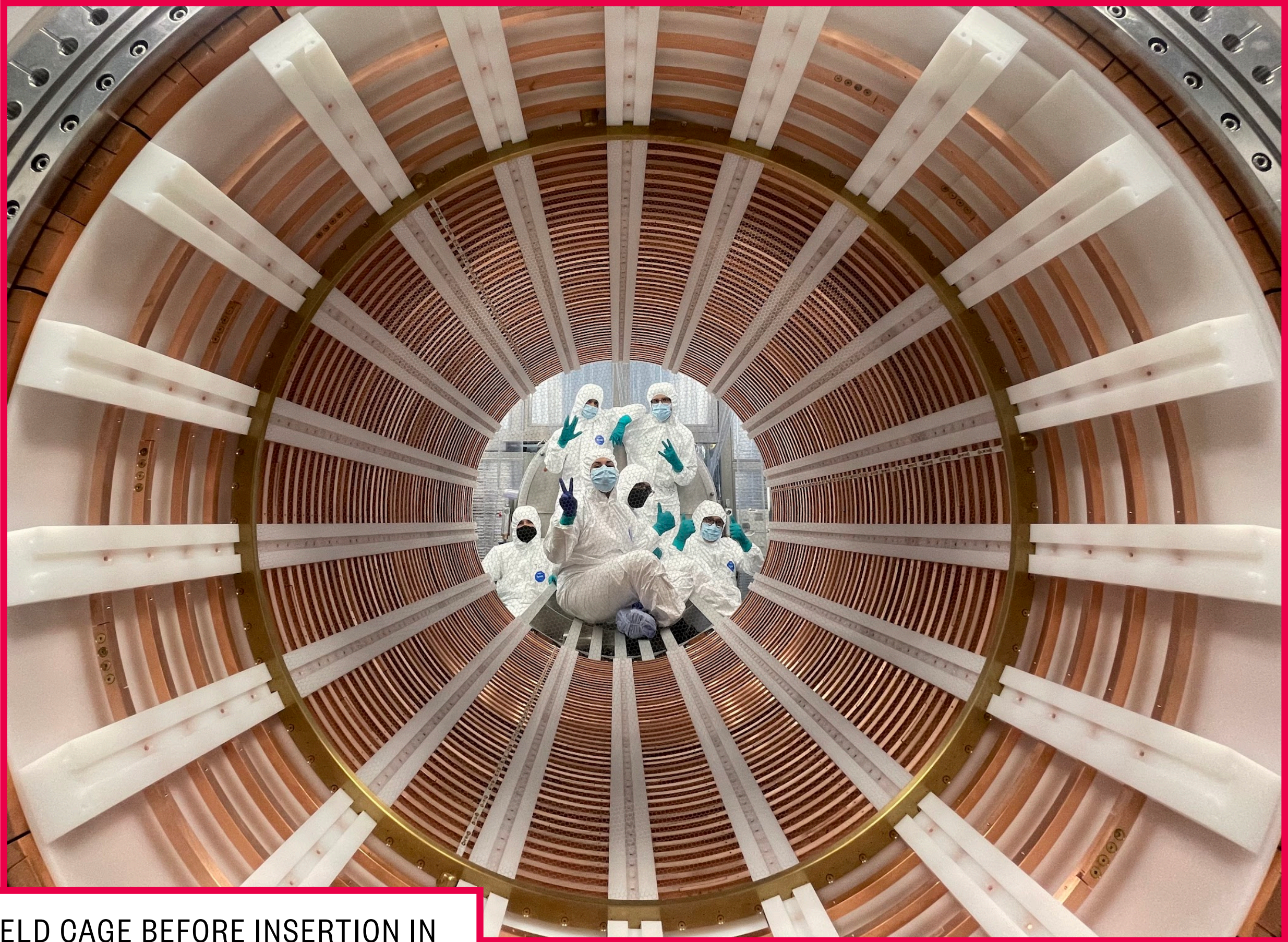
FIELD CAGE ASSEMBLED



DETAIL OF THE EL REGION

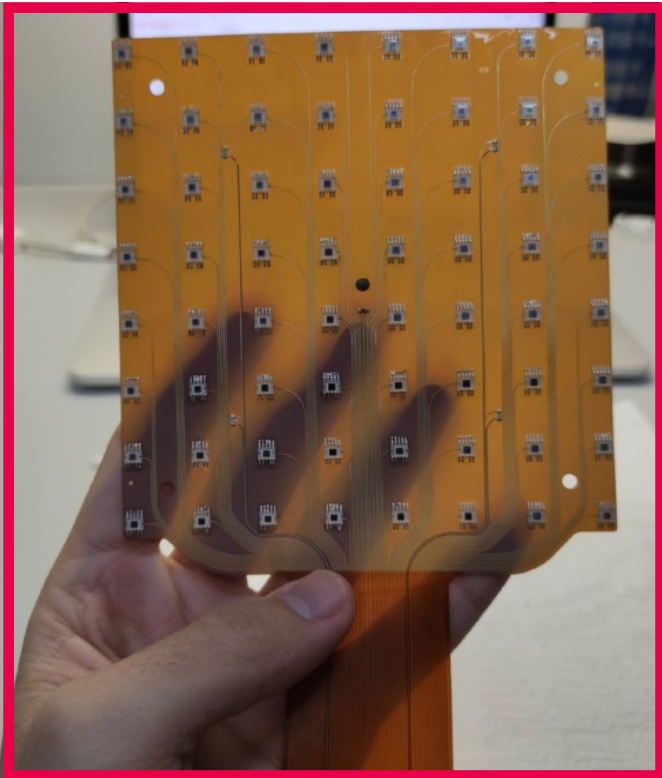
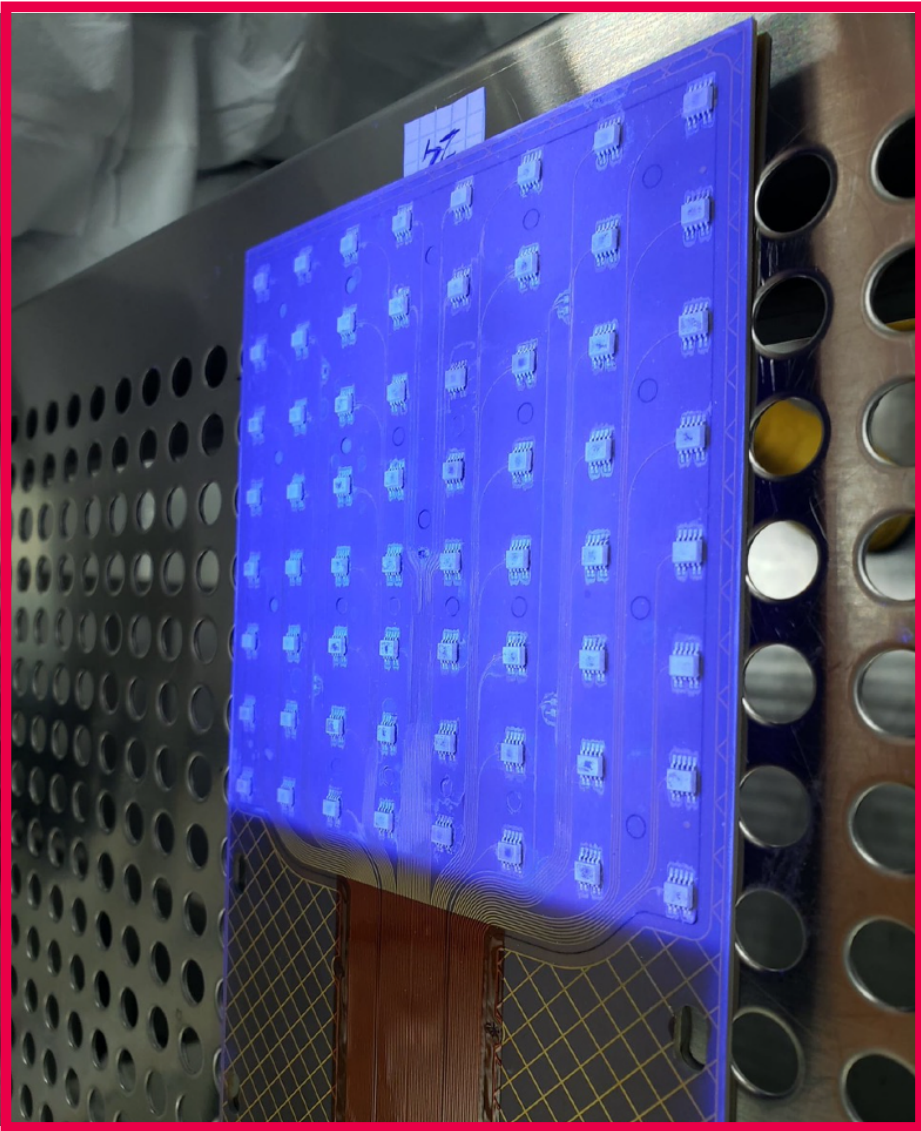


FIELD CAGE BEFORE INSERTION IN PRESSURE VESSEL



NEXT-100

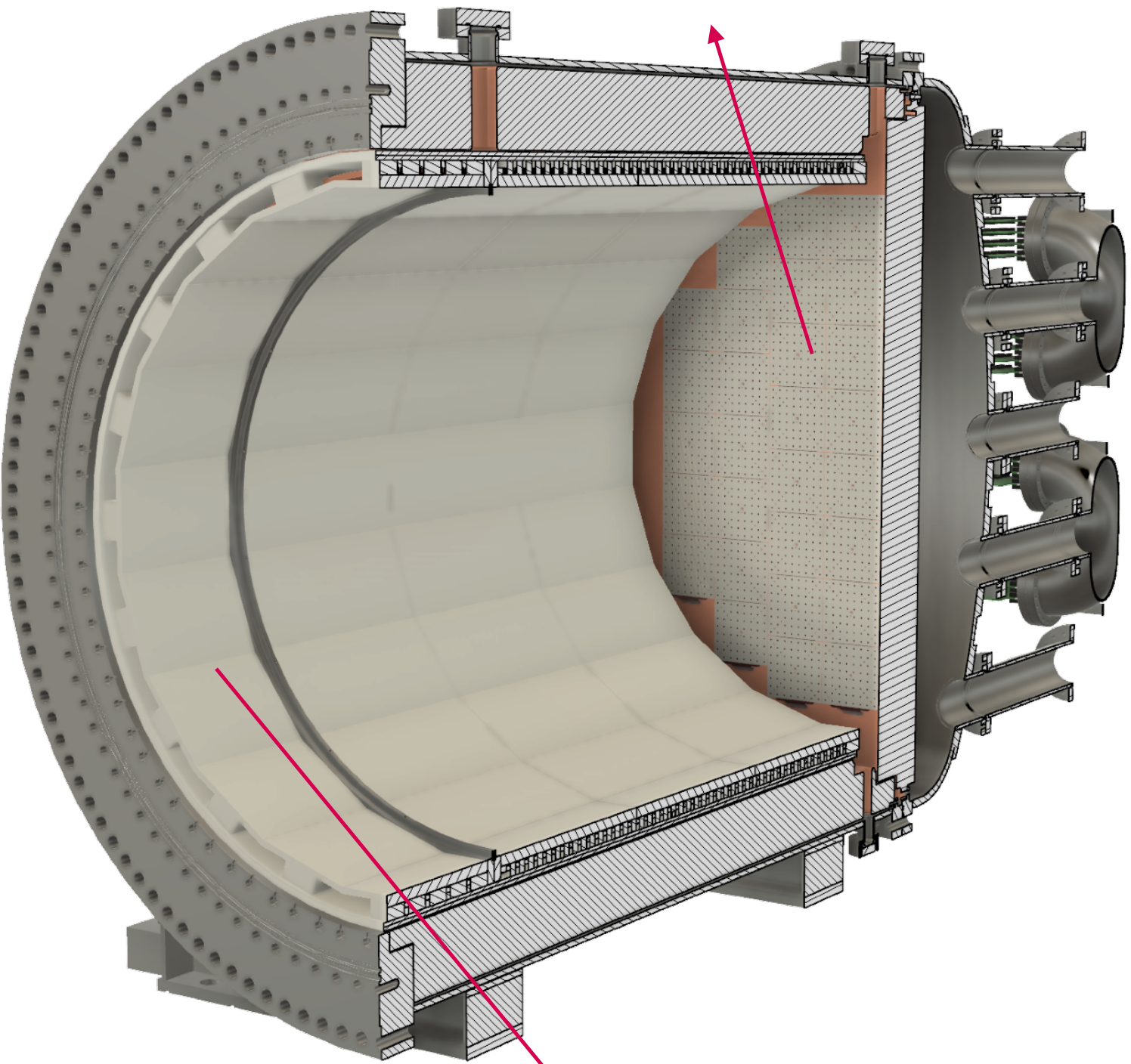
67



Hamamatsu SiPMs:
easier to mount,
more robust,
larger area.
Better for
dynamic range

Coated with TPB
for better light
detection

Tracking Plane
3584 Hamamatsu SiPMs
1.3x1.3 mm² - 15.55 mm pitch
(60% more photons)



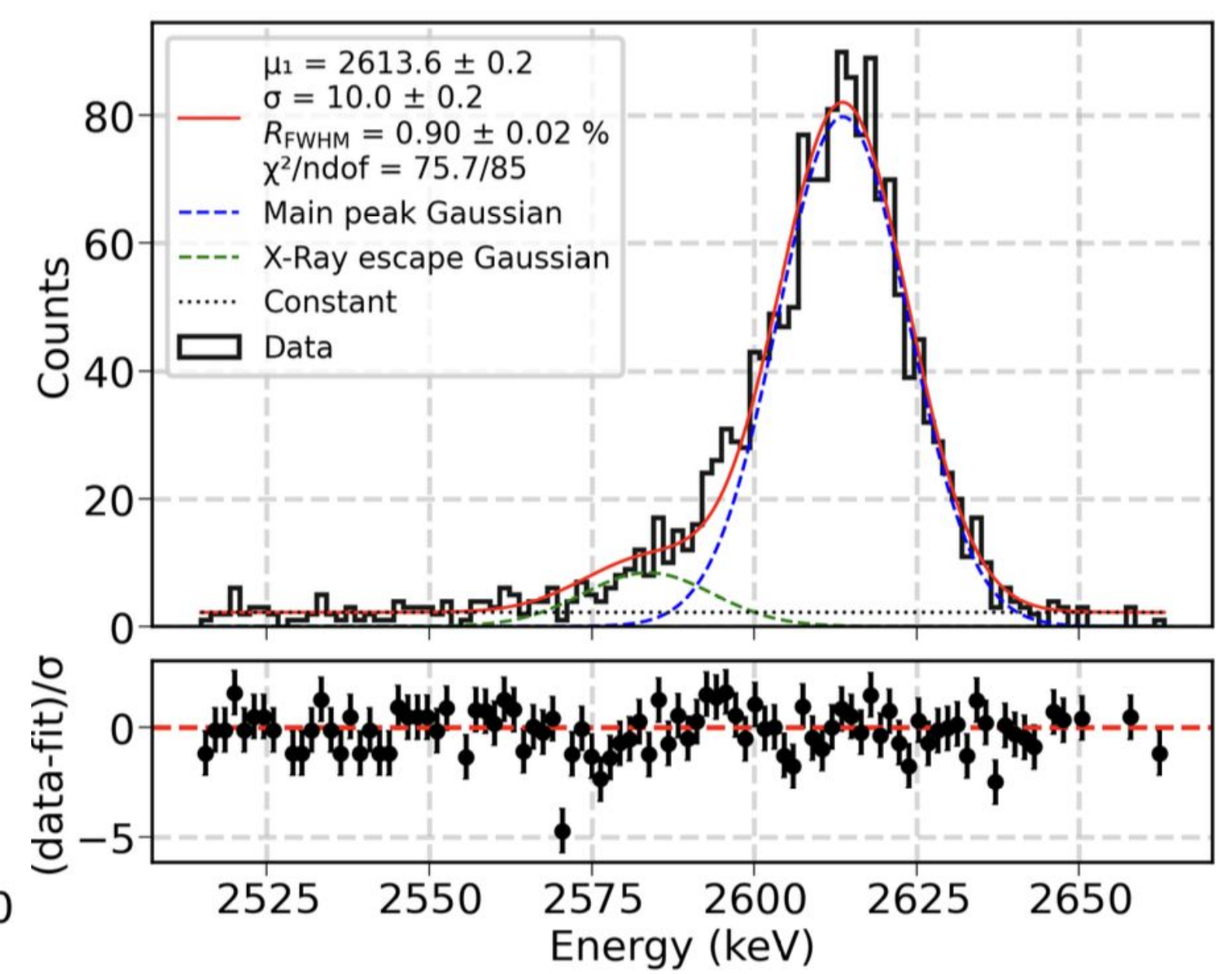
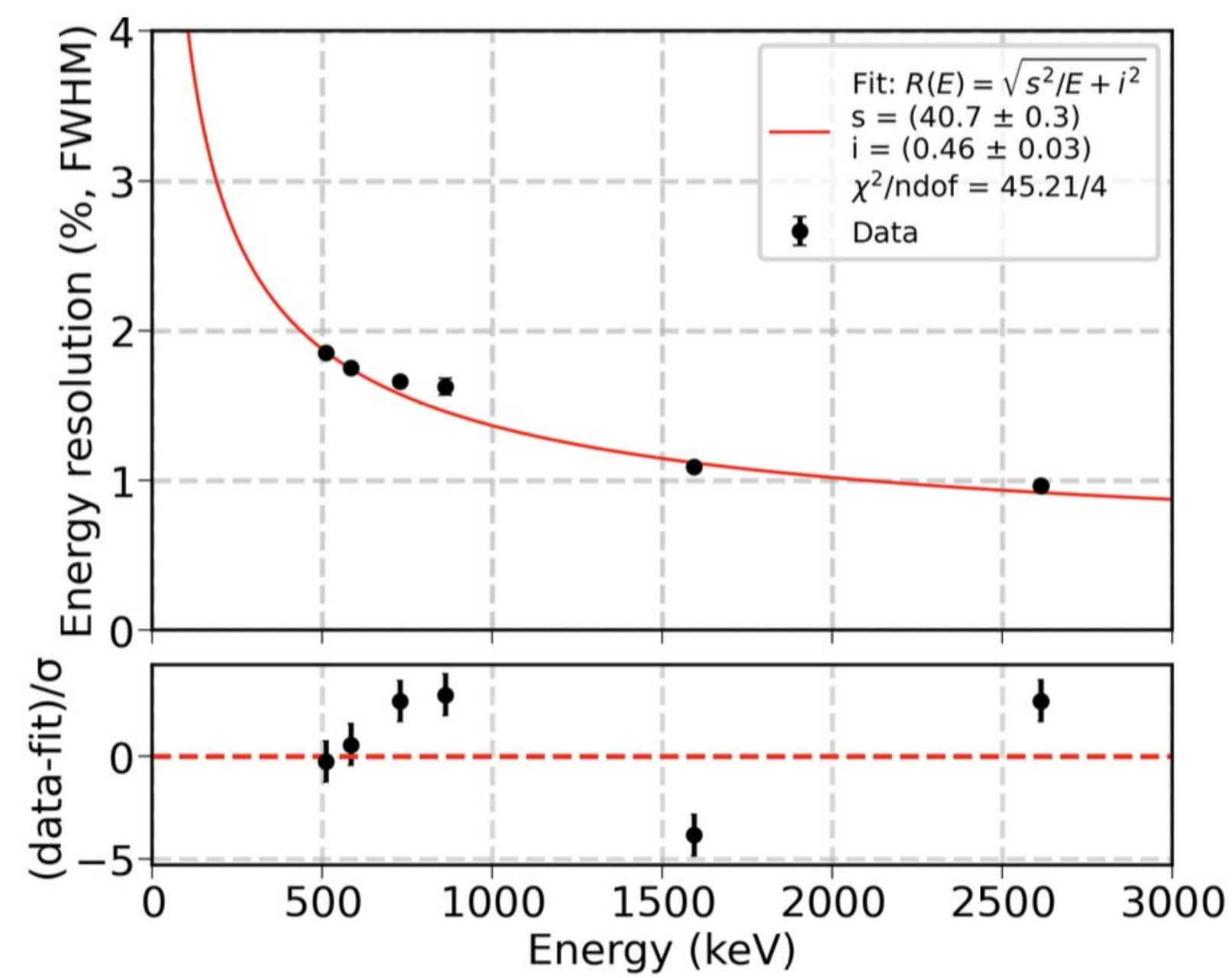
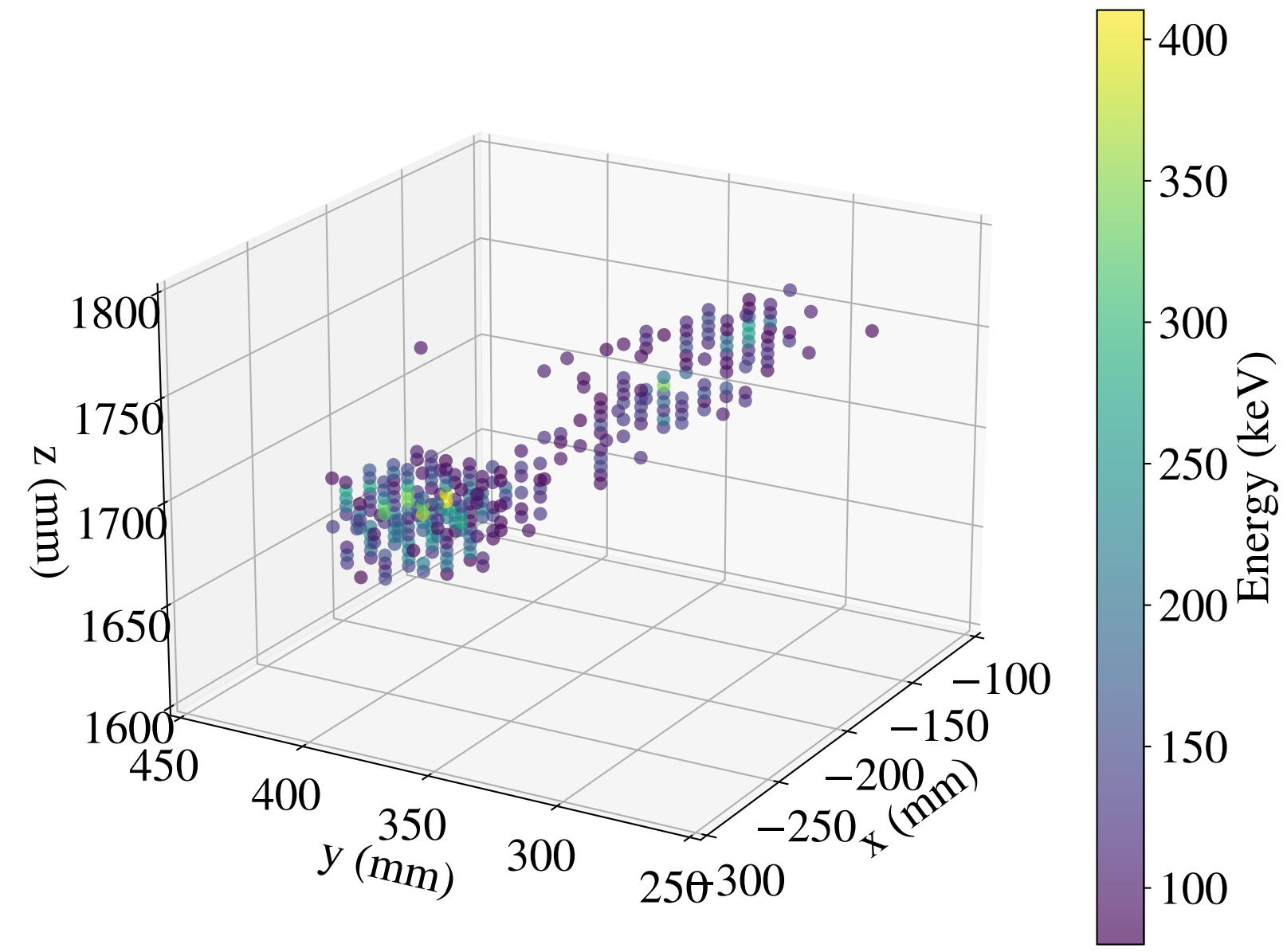
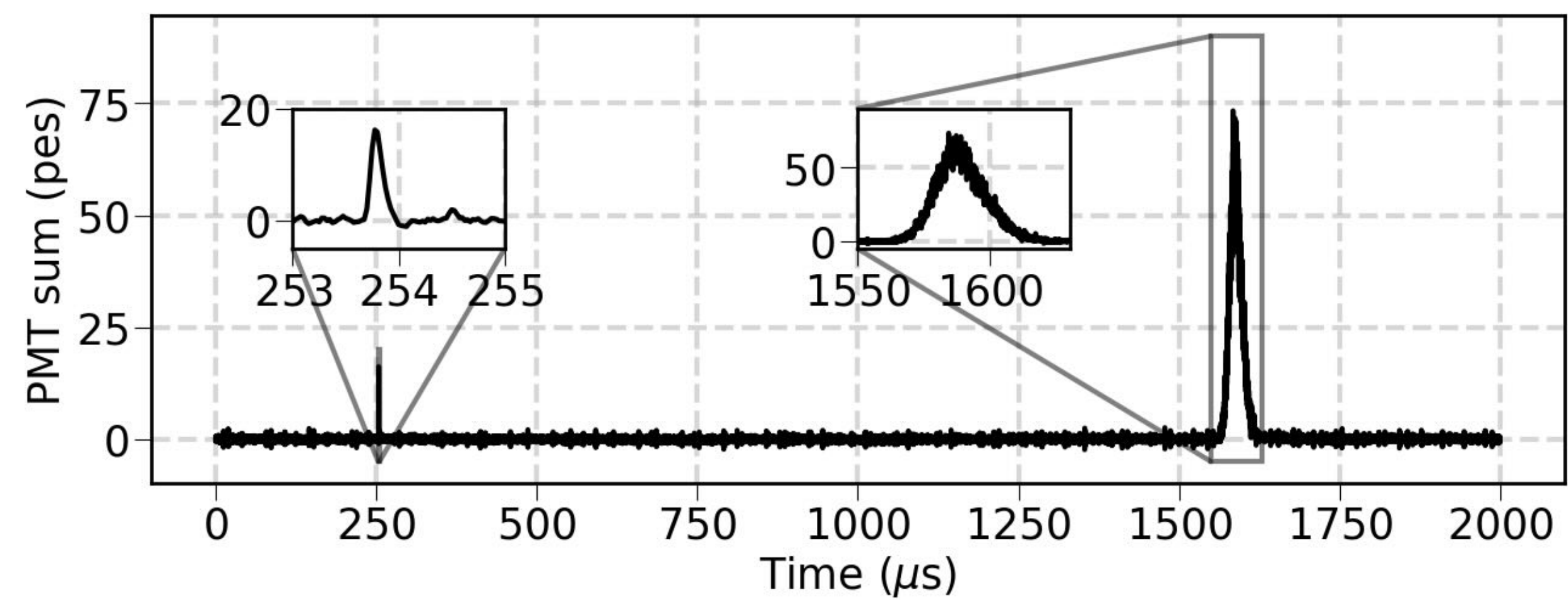
Energy Plane
60 Hamamatsu PMTs
R11410-10 - Same NEW
(30% coverage)

PMTs coupled
to xenon gas
through
sapphire
windows
welded to a
radio pure
copper frame



WINDOWS ARE COATED
WITH PEDOT

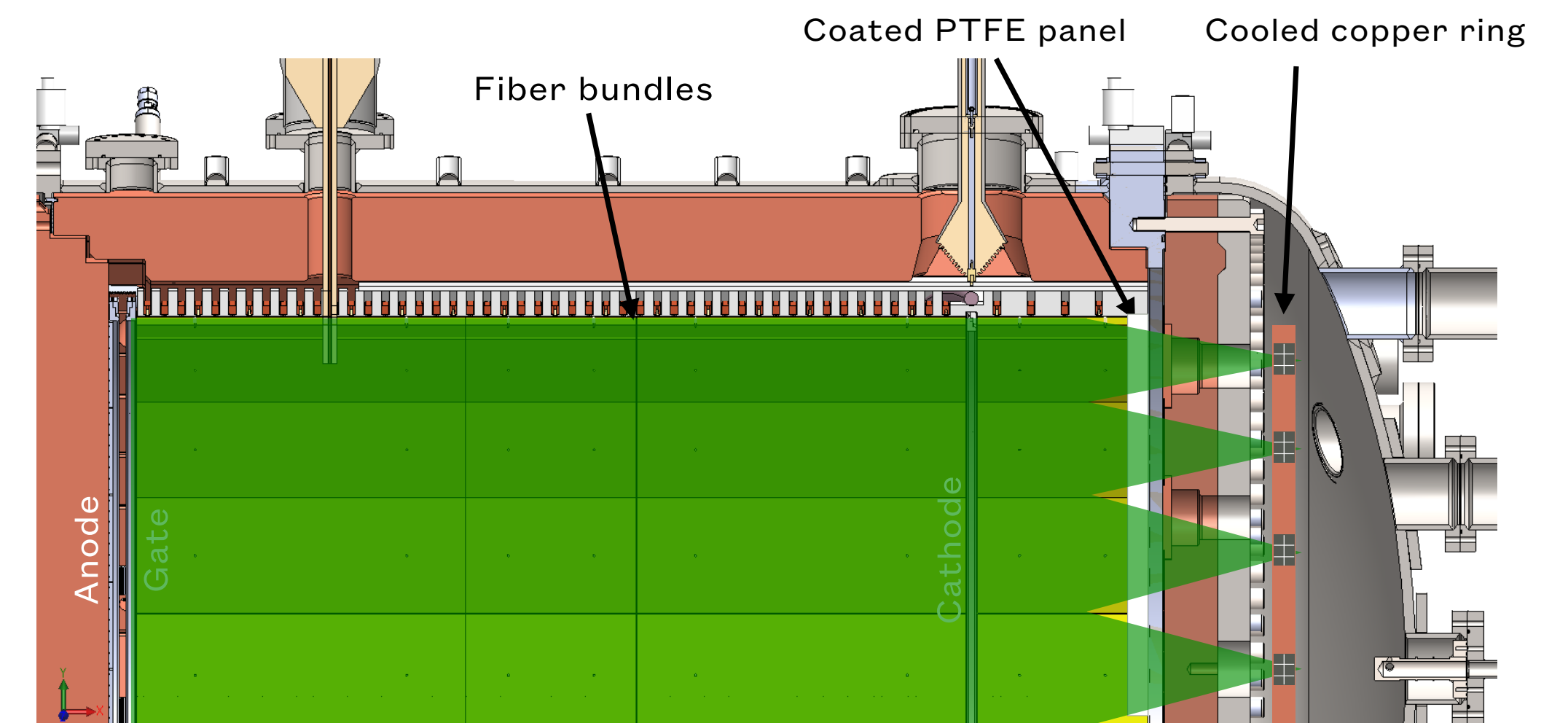
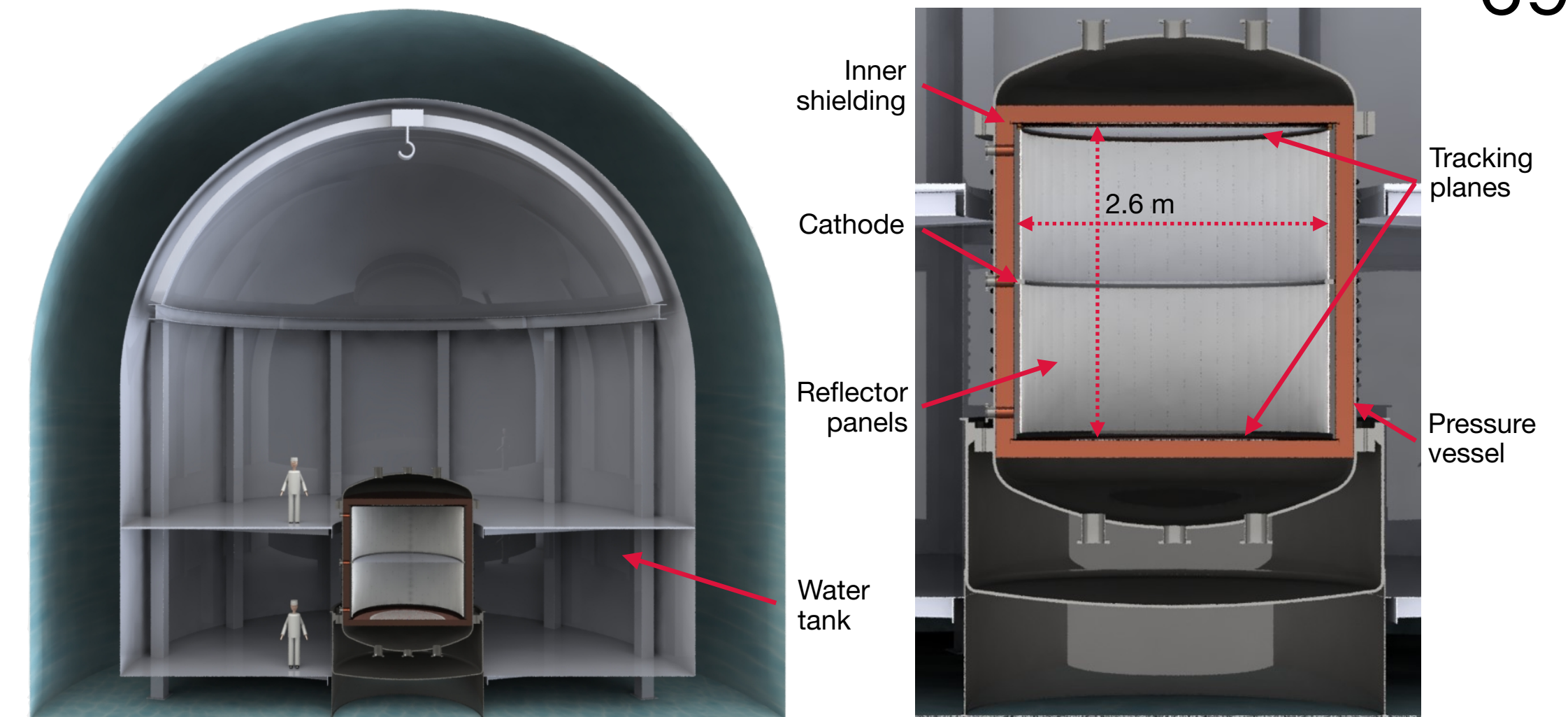
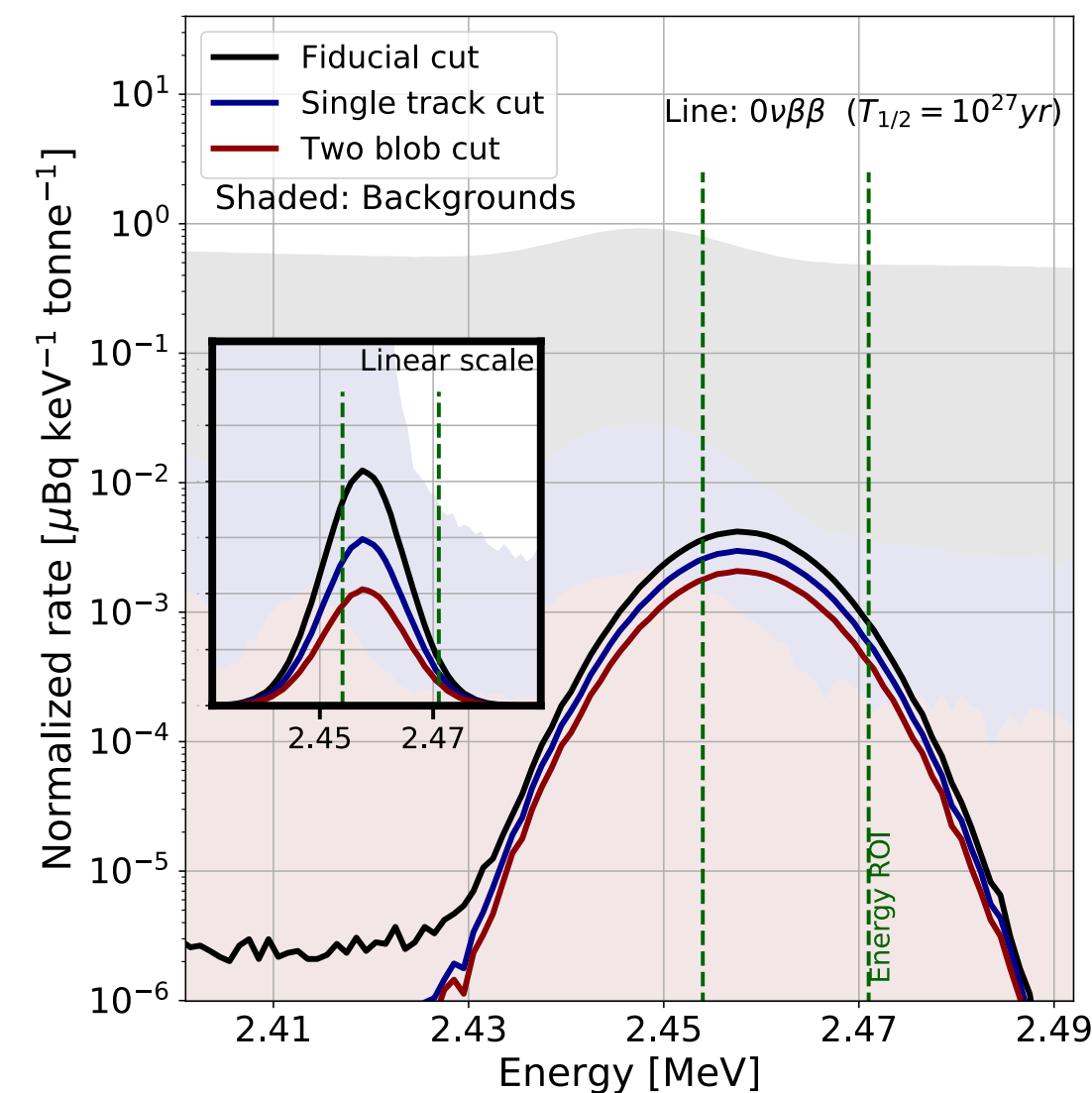
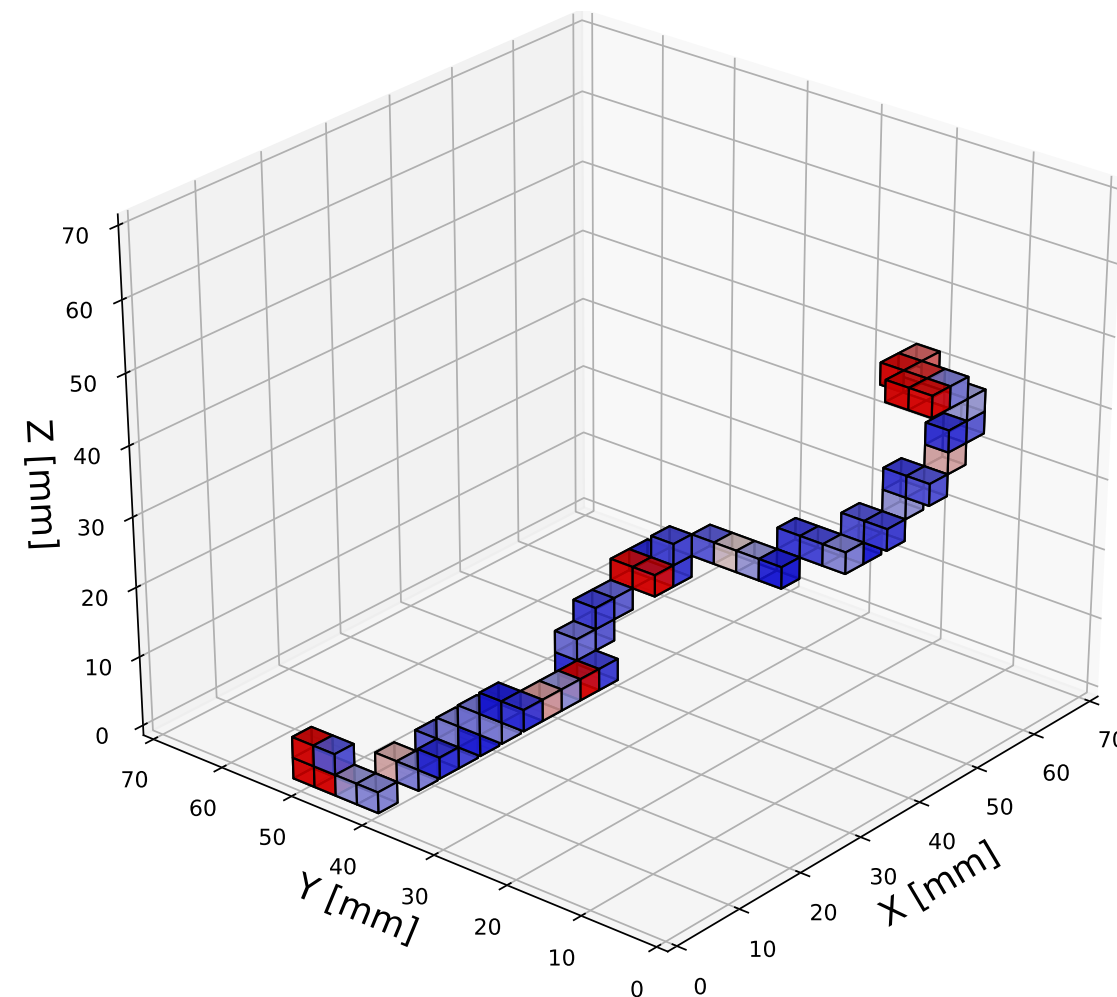




arXiv:2511.02467

NEXT-HD

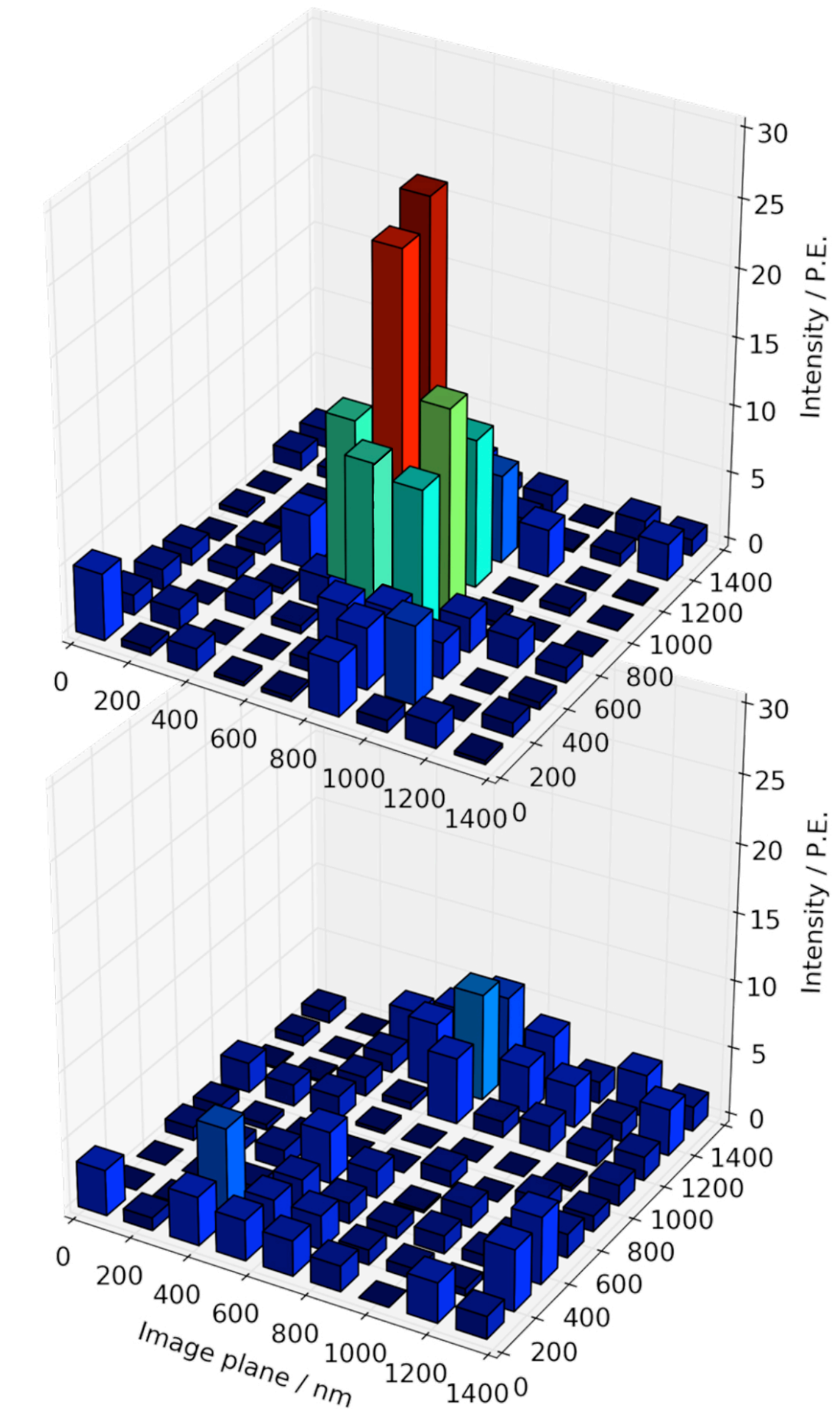
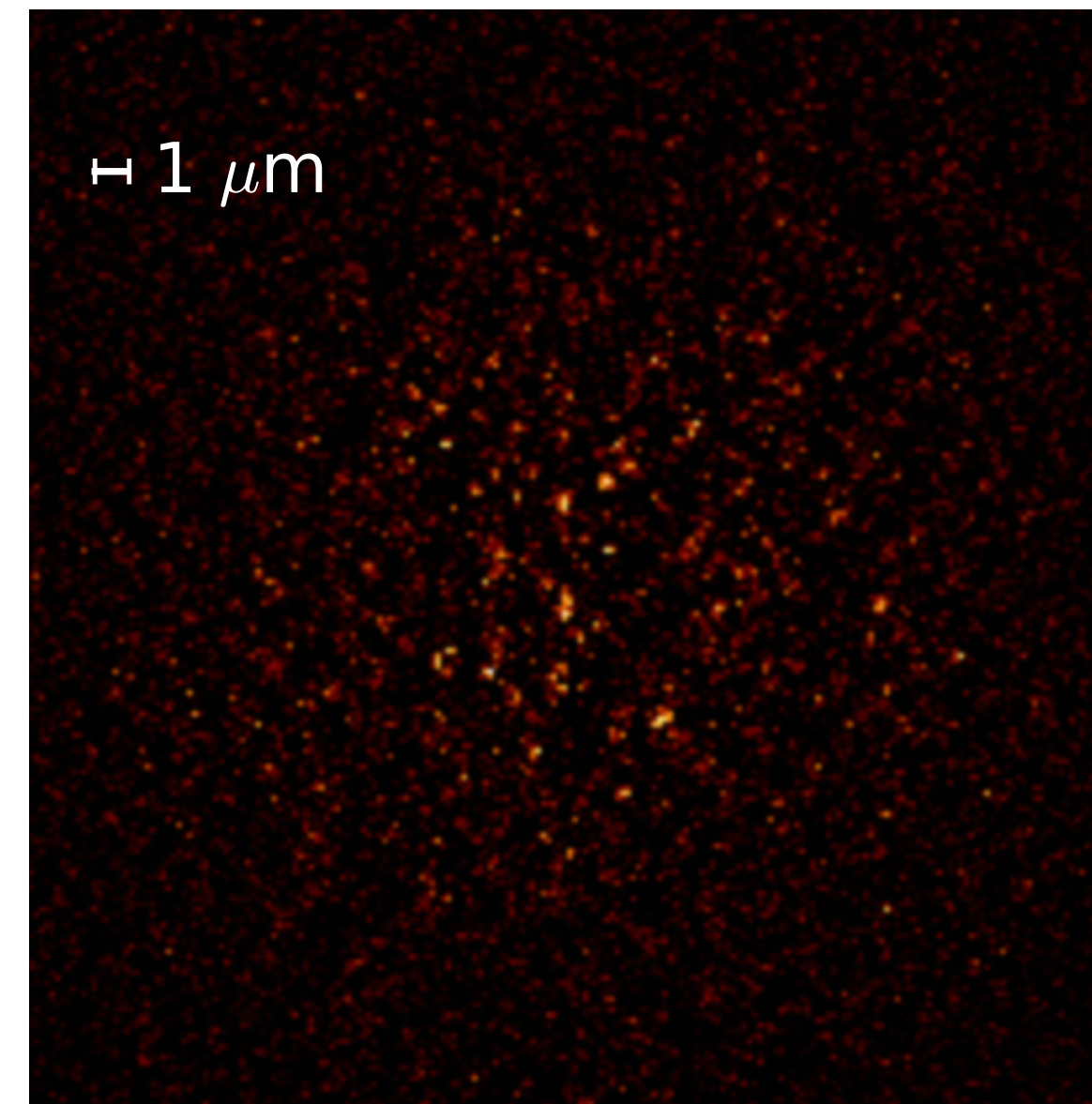
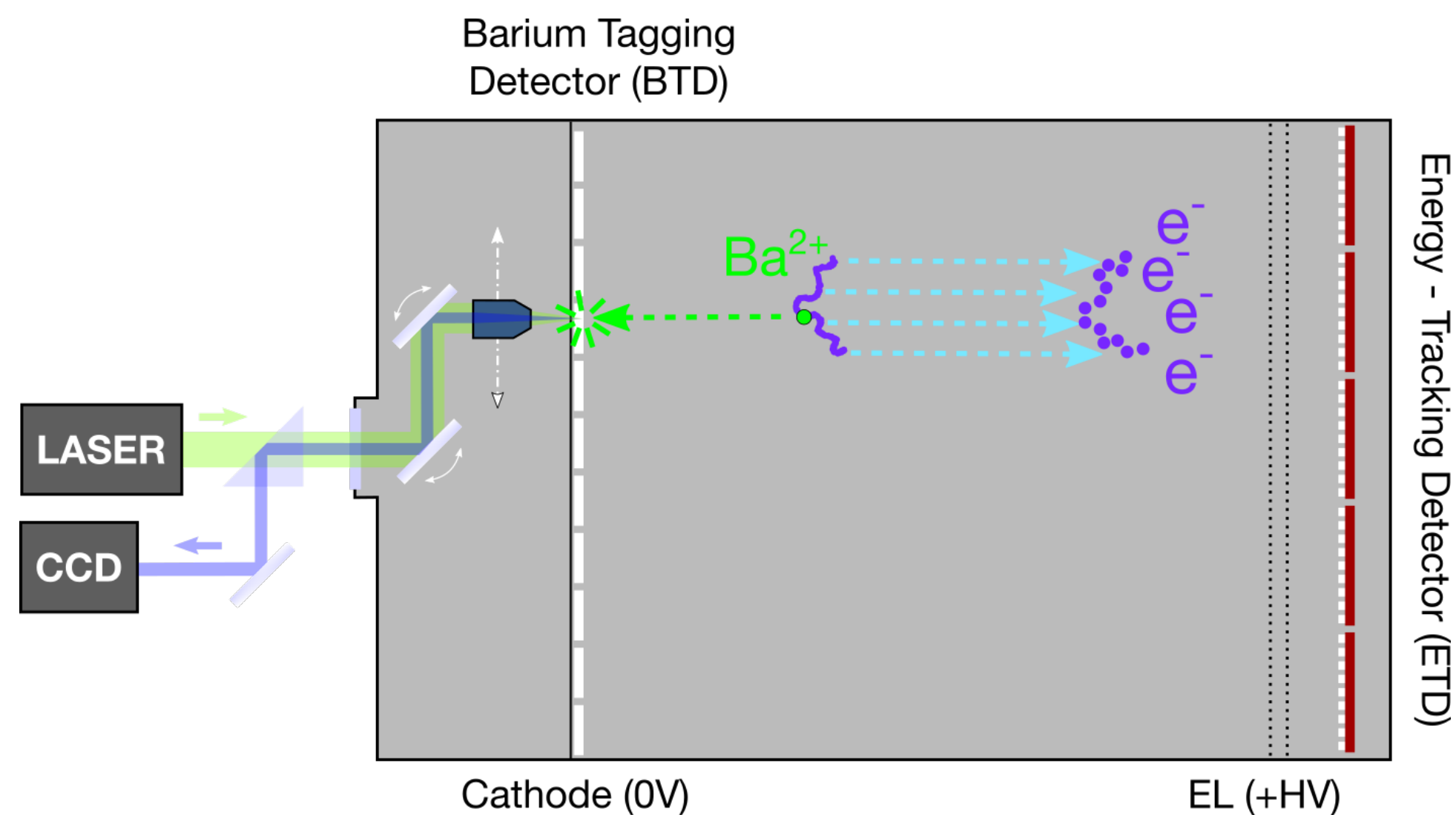
- **Experimento multi-módulo** con un primer detector de 1 tonelada de ^{136}Xe en el Laboratorio Subterráneo de Canfranc.
- Diseño base: **TPC simétrica** con cátodo central, lectura mediante un **plano denso de SiPMs** y un **barril de fibras centelladoras**.
- Fondo estimado: 0.09–0.27 cuentas / ROI / ton / yr.



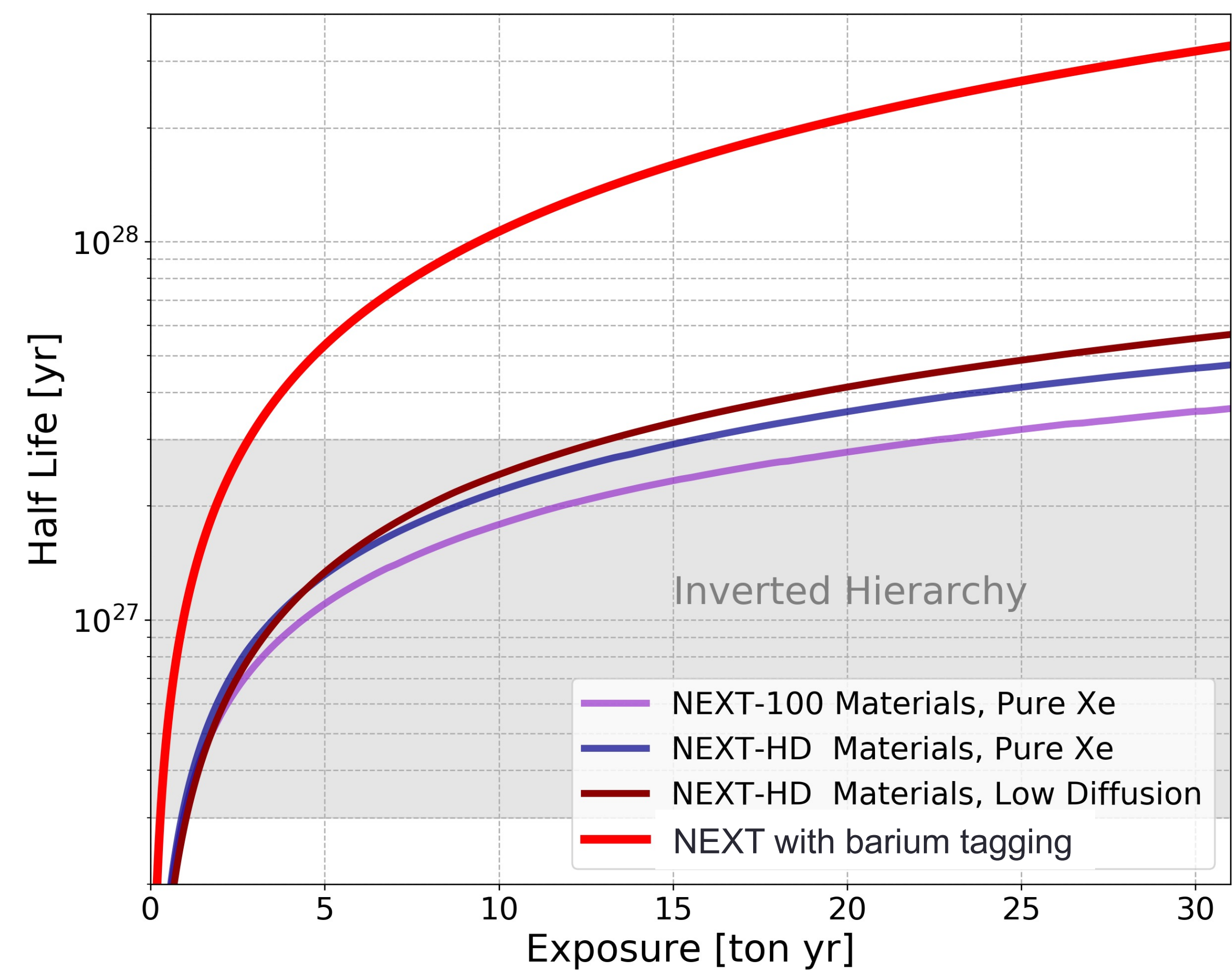
NEXT-BOLD

70

- El desarrollo de un sistema eficiente y escalable de **identificación de iones de bario** en xenón gaseoso a alta presión posibilitaría un **experimento libre de fondos**.
- NEXT utiliza *single-molecule fluorescence imaging* (SMFI) para detectar el ion Ba^{2+} producido en las desintegraciones doble beta.



SENSIBILIDAD DE NEXT EN LA ESCALA DE LA TONELADA



Summary

72

Neutrinoless double beta decay searches are the most promising way to establish that neutrinos are Majorana particles.

The current generation of experiments is exploring the degenerate region of neutrino masses. Going forward, double beta decay experiments will require exposures well above 10^3 kg yr and background rates below 1 counts tonne⁻¹ yr⁻¹.

NEXT has proven that a GXe TPC can provide both high energy resolution and tracking for event identification. NEXT-100 will probably be the most sensitive experiment using ¹³⁶Xe, according to the background rate measured in NEXT-White.

There's a clear path to improve NEXT towards the ton scale: reach energy resolutions close to the intrinsic limit (<0.5% FWHM) and improve the rejecting power of the tracking signature.

R&D on chemical tagging of Ba ions undergoing, with very promising results so far.